

DIASTROPHIC EVOLUTION
OF
WESTERN PAPUA AND NEW GUINEA

by

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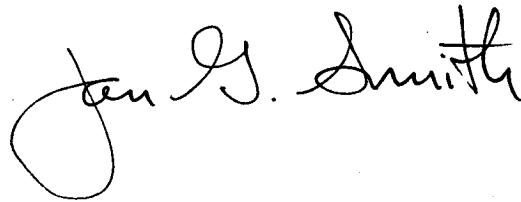
A thesis submitted in partial fulfillment
of the requirements for the

Degree of Doctor of Philosophy

UNIVERSITY OF TASMANIA
HOBART

July 1964

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university and to the best of my knowledge and belief contains no copy or paraphrase of material previously published or written by another person except where due reference is made in the text of the thesis.

A handwritten signature in cursive script, reading "Jan G. Smith". The signature is written in dark ink and is positioned below the main body of text.

JAN G. SMITH

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July 1964

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Map

1. Territory of Papua and New Guinea with alphabetical index to geographical names..In pocket

ABSTRACT

There are four main phases in the diastrophic evolution of western Papua and New Guinea: (1) a Mesozoic phase of taphrogenesis (geosyncline formation) characterized by the fragmentation of a pre-Mesozoic cratonic platform into a series of intrageosynclinal troughs and geanticlines which constituted the Papuan geosynclinal system. This phase was accompanied by basic volcanism and ultrabasic plutonism. (2) A Paleogene phase defined by the temporary stabilization of the geosynclinal system and the development of an extensive quasi-platform regime. (3) A Lower and Middle Miocene phase of retrogressive taphrogenesis marked by remobilization of the earlier geosynclinal terrain and again by important volcanism. (4) An Upper Miocene to Recent orogenic phase dominated by the uplift of the Papuan geosynclinal system to form the New Guinea cordillera. Uplift was associated with the formation of an exogeosynclinal trough, foreland folding and andesitic volcanism.








The Papuan geosynclinal system is thought to have formed primarily as the result of extensional stresses within the earth's crust, although there is strong evidence that simple shear, translation and rotation have also contributed to the total deformation of the orogen. These fundamental horizontal movements have served as a framework for the intense vertical oscillations that characterized the development of the Papuan geosyncline and the adjacent platform. The vertical movements culminated in

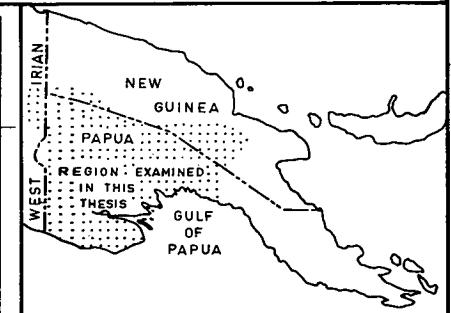
the uplift of the New Guinea cordillera and the formation of two distinct patterns of folding and faulting. The first type of folding is of a secular nature and is intimately linked with the uplift of the orogen. These primary folds are represented by the large horst-like anticlinoria which form the backbone of the main cordillera. The second type of folding is episodic in nature and is the secondary consequence of orogenic uplift. These are the foreland folded structures of the Papuan foothills which originated as the result of gravity sliding off the flank of the rising orogen.

GEOLOGIC SKETCH MAP
WESTERN PAPUA AND NEW GUINEA

This map illustrates the geological structure of Western Papua and New Guinea. Key features include:

- Major Rivers:** Digul River, Kapi River, Strickland River, Aramia River, Fly River, Ramu River, Kaugel R., Erave R., Kikori River, Turama River, and Bomu River.
- Mountain Ranges and Peaks:** Doma Peaks, Mt. Rentaul, Mt. Kerewa, Mt. Sisa, Mt. Bosavi, Mt. Giluwe, Mt. Ialibu, Mt. Hagen, Mt. Karimui, Mt. Yellia, and the Aird Hills.
- Lakes:** Lake Kutubu, Lake Tebera, and Lake Murray.
- Geological Features:** Marum ultrabasic belt, various numbered geological units (e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45), and various numbered locations (e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45).
- Coastal Features:** Morehead, Mabaduan, and Hohoro.
- Scale and Coordinates:** A scale bar indicates 0 to 100 KM. The map includes latitude lines from 5°S to 9°S and longitude lines from 141°E to 145°E.

- | | |
|---|--------------------------------------|
|  | QUATERNARY COVER |
|  | QUATERNARY VOLCANOES AND VOLCANICS |
|  | PLIOCENE AND UPPER MIOCENE |
|  | MIDDLE AND LOWER MIOCENE ; PALEOGENE |
|  | MESOZOIC |
|  | CRYSTALLINE BASEMENT |
|  | WELL SITES |



JGS 1963

INTRODUCTION

This dissertation is a synthesis of the nature, processes and evolution of the diastrophism which is manifest in the lowlands and mountainous regions of western Papua and New Guinea. It is based on a critical examination and evaluation of a wealth of stratigraphic and structural information which has been gathered in this region by petroleum exploration companies since 1911.

Nature and purpose of study.-- Since the discovery of oil seepages at the mouth of the Vailala River in 1911 extensive exploration programs in search of petroleum have been carried out in the Territory of Papua and New Guinea. As a result of these investigations a tremendous amount of stratigraphic and structural information has been assembled. However, much of this information has lain fallow for many years; it has never been compiled in such a manner as to convey a lucid and concise picture of the diastrophic evolution of the New Guinea orogenic system, particularly not in terms of contemporary concepts of geosyncline formation and mountain building.

In order to make good use of this data Professor S. Warren Carey with the co-operation of the Australasian Petroleum Company, Oil Search Limited, Papuan Apinaipi Petroleum Company and the Commonwealth Bureau of Mineral Resources initiated a research program at the University of Tasmania late in 1961 which was to be devoted to a geotectonic study of Papua and New Guinea. The ultimate aim of the study is to prepare a comprehensive synthesis of the processes and evolution of diastrophism in Papua and

New Guinea which, when completed, will represent a valuable contribution to knowledge of tectonism in the Melanesian region of the circum-Pacific mobile belt and to the general understanding of geotectonic problems.

This research program, which has been appropriately designated as the Papuan Tectonic Project, is thus far comprised of two main phases of investigation. In the first place one group of workers has been engaged in an examination and synthesis of the existing geological data in order to achieve the objectives outlined above. A second group has concentrated on geophysical aspects of study and is collecting a considerable amount of new gravity data, as well as reviewing the older geophysical information which was assembled in the course of petroleum exploration.

The geological research team consists of three post-graduate students at the University of Tasmania; R.Pitt, A.Kugler and myself, each of whom have been studying a particular region of Papua and the adjacent parts of New Guinea; viz., the Lakekamu embayment, Kukukuku lobe and the hinterland of western Papua north and west of the Gulf of Papua, respectively.

Location.-- This dissertation is particularly concerned with the tectonics of a very extensive region of western Papua and the adjacent parts of the Territory of New Guinea (Plate 1, Map 1). The region consists of about 200,000 square kilometers of marshland, foothills and very high mountains which are situated between longitudes 140°E . and 145°E . On the south this region is bordered by the Gulf of Papua and the Torres Strait. It extends northward to the crest of the main New Guinea cordillera.

Method of study and presentation.-- Research has been conducted in several stages. The first stage of investigation was carried out early in 1962 when members of the Papuan Tectonic Project under the leadership of Professor S. Warren Carey and Mr. G. A. V. Stanley, formerly of the Australasian Petroleum Company, visited many of the most important structural and stratigraphic localities in Papua and New Guinea. This experience provided considerable insight into the nature of the geological problems throughout New Guinea which in turn formed a firm practical basis for subsequent study.

The second main phase of investigation was conducted at the University of Tasmania and to some extent in the offices of Oil Search Ltd. in Sydney and Mines Administration Ltd. in Brisbane. At this time virtually all records of geologic exploration carried out in Papua and New Guinea were at the disposal of the research team. This host of information was reviewed, evaluated and compiled in preparation for the third phase of study.

The final phase of this investigation has been devoted to achievement of the ultimate goal of the Papuan Tectonic Project; i.e., interpretation and synthesis of this geologic information in terms of the processes and history of diastrophism in western Papua and New Guinea. Specifically, this study entailed a study of the nature and distribution of sedimentary rocks in Papua and was aimed at unraveling the diastrophic framework and evolution of the region. This work represents the first main part (Section 1) of this dissertation.

In turn these gross diastrophic patterns and the more superficial deformations superimposed on them;

namely, folding and faulting, were analyzed in order to provide the basis for some inferences concerning the nature of the processes which governed the development of the geosynclinal system and the uplift of the New Guinea orogen. The last three principal sections of the thesis are devoted to study of these problems.

Previous work.-- Information concerning the geology of the Territory of Papua and New Guinea is of two types. The first type has accumulated as the result of petroleum exploration and for the most part is unpublished.

On the other hand there is very little published information available. The Geology of Papua which was published by E.R. Stanley in 1923 was the first attempt at a comprehensive report. In addition to this major work only a few other specific papers were published in the period between 1911 and 1950. In 1950 a chapter was devoted to Australian New Guinea in The Geology of the Commonwealth of Australia by T.W.E. David. In the same year M.F. Glaessner published a paper dealing with the position of New Guinea in the geotectonic framework of the Melanesian region of the Pacific. Carey (1938b; 1958) has pointed out several of the most significant tectonic features of the island and their relation to his orocline concept. In 1961 the Australasian Petroleum Company published in the Journal of the Geological Society of Australia a strictly descriptive, largely stratigraphic, summary of their extensive geological exploration in western Papua between the years 1937 and 1961. In recent years the Bureau of Mineral Resources, Geology and Geophysics of the Commonwealth of Australia has published several reports which shed considerable light on the geology of Papua and New Guinea.

A very comprehensive geologic review of the former Netherlands New Guinea has been prepared recently by W.A. Visser and J.J.Hermes (1962). Unfortunately, the report did not become available in Hobart until this dissertation was in the final stages of preparation; consequently, their information has not been used to its fullest advantage.

Acknowledgments.-- I am pleased to acknowledge the supervision given to me by Professor S.Warren Carey of the University of Tasmania whose constant interest, penetrating criticisms and outstanding geologic insight were a great asset in the preparation of this dissertation. G.A.V.Stanley made many generous and helpful contributions to my understanding of the geology of Papua and New Guinea. Considerable thanks are due to my friends and associates on the Papuan Tectonic Project and at the University of Tasmania, particularly A.Kugler, R.P.B.Pitt and J.E.Shirley, who proffered abundant advice, criticism, encouragement and general moral support.

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1 DIASTROPHIC FRAMEWORK OF WESTERN PAPUA AND NEW GUINEA

Krumbein and Sloss (1951;p.318) have defined the tectonic framework of sedimentation as "the combination of subsiding, stable and rising tectonic elements in sedimentary source and depositional areas." The first part of this dissertation is devoted to study of such combinations of movement that are manifest in the Mesozoic and Tertiary sedimentary sequences of the so-called Papuan Basin (Osborne, 1956). However, in this context I prefer to use the term diastrophic rather than tectonic because it conveys a far more general connotation including deformation of the earth's crust at all scales ranging from folding and faulting, through geosyncline formation and mountain building as well as continental and oceanic disturbances. At least in some circles the term tectonic has a more restricted meaning which will be considered presently.

In the subsequent pages I will describe and analyze the lithology, thickness and distribution of the rocks constituting each of the main stratigraphic intervals occurring in western Papua. On the basis of this work it will be possible to make certain inferences concerning the nature, intensity and distribution of crustal movements which controlled sedimentation. The main distinctions which will be made here are between platform areas on one hand and the far more mobile geosynclinal regimes on the other hand. Once the diastrophic framework of sedimentation

and its variation between different stratigraphic intervals are established, then, it will be possible to make further inferences regarding the origin and subsequent deformation of these diastrophic elements; i.e., platforms, geosynclines, geanticlines and orogens.

The diastrophic framework has been established for each of the ten main stratigraphic intervals present in western Papua and New Guinea; namely, Quaternary; Pliocene; Upper, Middle and Lower Miocene; Paleogene; late and early Cretaceous; Jurassic and the Permo-Triassic. The analysis is made in the above order; i.e., from the youngest to the oldest units. In my view there are several advantages in this method of treatment. One of the foremost advantages is that for the analysis of any stratigraphic unit one has already some notion of the post-depositional processes, such as uplift and erosion, folding, metamorphism that may have affected the unit under examination. Consequently, it is relatively easy to make allowances for these impressed characteristics. Finally, the information concerning the younger rocks is generally more reliable and complete; thus, it forms a sound basis for extrapolation into the past.

Two maps have been prepared for each stratigraphic interval considered. The nature and distribution of the rocks in question are summarized by an isopach and lithofacies map. The dominant lithologic aspect of the rocks is illustrated since in most cases neither the distribution nor the quality of information warrants a more sophisticated treatment which might be based on averages or ratios of textural or compositional characteristics. A diastrophic framework map has been prepared for each stratigraphic interval which is based on the diastrophic implications of the lithofacies and isopach maps.

In reconstructing the diastrophic framework of western Papua and New Guinea the principal distinction will be made between negative regions of deposition and positive source regions. The negative regions will in turn be differentiated into geosynclinal zones and platforms. Unless specified otherwise the term geosyncline will be used to imply the extracratonic orthogeosyncline of Kay (1951). In Papua, as in most mobile regions, the geosyncline is thought to have consisted of a series of basins or intrageosynclinal troughs separated by narrow ridges or geanticlines. Because of this rather complex internal structure, I will refer to the entire orthogeosyncline as the Papuan geosyncline and use more local terminology for the troughs.

In several instances throughout the text it will be necessary to make a distinction between eugeosynclines and miogeosynclines. The term eugeosyncline will be used to mean the highly mobile axial zone of the orthogeosyncline which is generally associated with some volcanism. On the other hand the term miogeosyncline will be used to denote the, often discontinuous, portions of the orthogeosyncline that are transitional between the eugeosyncline and the relatively stable cratonic platform. The miogeosynclinal regime is devoid of volcanism.

The processes of geosyncline formation will be called taphrogenesis, much in the sense of Bucher (1933, p.140 and 340).

In contrast to the strongly negative, highly mobile geosynclinal furrows, a large part of the western Papuan sedimentary sequence was deposited on a platform. The platform or shelf diastrophic environment is characterized

by slow, rather weak oscillatory movements; i.e., alternation between subsidence and emergence.

The positive movements in the sedimentary source regions of Papua have been of two kinds: positive movements of geanticlinal swells during the dominantly geosynclinal phases of diastrophism when negative movements were paramount and the extensive positive movements which are the main element in the orogenic or mountain building phases of diastrophism. The terminology related to these latter movements warrants special consideration at this point.

Most commonly used terms which denote the processes of mountain building such as orogenesis and tectogenesis, which are perfectly good terms within the limits of their original definitions, have in general been misused to such an extent by many geologists that the meanings have become quite vague. Consequently, the value of these terms as used in a considerable amount of geologic literature approaches zero.

The following discussion is not an attempt to revitalize or redefine this terminology but is rather an attempt to state the terms that I will use and the connotations that will be attached to them.

Gilbert (1890) applied the word orogeny to the process of forming mountains, particularly by folding and thrusting. Later Haarmann (1930) recognized a tectogenic phase in mountain building which included the processes by which rocks are deformed. These he differentiated from processes resulting in morphological features which he called orogenesis. Von Bubnoff (1954) and many others have followed Haarmann in advocating this

terminology. De Sitter (1959, p.9) has preferred to use orogenesis in a broader context and has suggested the term morphogenesis for the phenomena producing the morphological features of mountains.

These distinctions, which have been made between the processes of rock deformation and the processes producing uplift and the external morphology of mountains, have stemmed from the fact that detailed examination of mountain belts in the past few decades and a better understanding of the relative rates of diastrophic movements have shown that considerable time often elapses between deformation and uplift. Furthermore, as de Sitter (1960) has emphasized, the zones of maximum deformation and subsequent uplift often are not coincident.

This is not the case in New Guinea, and I will show in a later section that the uplift and the associated morphological development of the orogen were very intimately related in terms of space to the internal or strictly tectonic structure of the mountain system. However, these processes, as we shall see, were not always concurrent in time. Therefore, there is a need to differentiate between these two basic processes. In this dissertation the terms orogenesis and mountain building will be used in the broadest sense including both the processes of deformation; e.g., folding and faulting, and also uplift which is accompanied by erosion and denudation. Where the need arises for a more specific connotation, the terms morphogenesis or merely uplift will be used for the processes resulting in the elevation and external development of the mountain system or orogen. Tectogenesis will refer to the processes of folding and faulting.

I must emphasize that it would be naive to think of morphogenesis and tectogenesis as completely separate entities. In reality they probably represent the end-members or poles of a whole spectrum of combinations, any of which may be generally referred to as orogenesis or mountain building. According to such a scheme either tectogenesis or morphogenesis could theoretically occur completely independently of the other or both processes could occur concurrently in varying degrees of intensity. Furthermore, the processes might occur in any order; e.g., morphogenesis preceding tectogenesis or vice versa.

1.1 QUATERNARY DIASTROPHISM

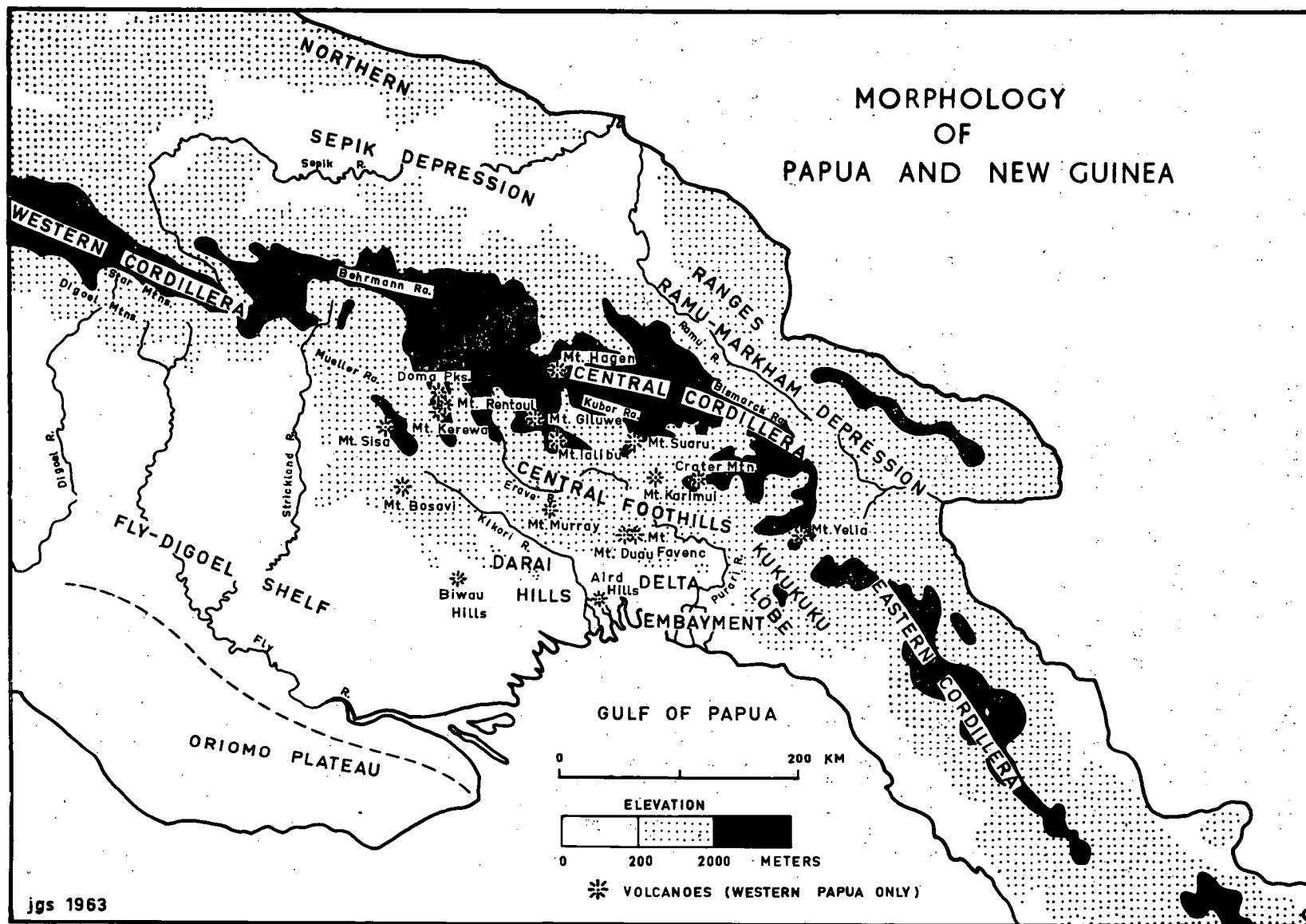
Western Papua and New Guinea can be divided into a series of distinct morphological provinces which reflect the various degrees of crustal instability which were manifest during the Quaternary phase of diastrophism (Fig.1). The main New Guinea cordillera, which forms the backbone of the island, was the site of the greatest amount of movement and there is much evidence to suggest that a large part of this great mountain system was shaped during the Quaternary. The mountain building movements were accompanied by intensive volcanism in western Papua. Furthermore, certain morphologic features of the entire region and the high seismicity along the northern margin of the main cordillera demonstrate that orogenic processes in western Papua and New Guinea are still quite active.

1.1.1 Morphology of Western Papua and New Guinea

Western Papua and New Guinea has been divided on the basis of external morphology into ten main provinces; viz., the Oriomo Plateau, Fly-Digoel shelf, Delta embayment, Darai Hills, central foothills, central cordillera, western cordillera, Kukukuku lobe, Sepik depression, Ramu-Markham depression and the northern ranges region. These subdivisions which are illustrated in Figure 1 will be used consistently throughout this study.

The main New Guinea cordillera or the "backbone", as it is sometimes called, extends westward from the

Figure 1



southeastern tip of the island for about 1800 kilometers to the western end of West Irian where it becomes entangled in the complex East Indian island arc system. This study deals with the central portion of the cordillera lying between longitudes 140°E. and 146°E. For the purposes of discussion this portion has in turn been divided into two subordinate segments: the central and western cordilleran regions.

Western cordilleran region.-- This term has been applied to a large (50-65,000 square kilometers) segment of the main New Guinea cordillera which lies between longitudes 143°E. and 140°E. It is bounded on the north by the Sepik depression and on the south by the Fly-Digoel shelf (Fig.1). The main ranges included in this division are the Star and Digoel Mountains, the Hindenburg, Victor Emanuel, Blucher, Mueller, Thurwald and Behrmann Ranges. More than fifty percent of this region is over 2,000 meters in elevation with culminations such as Juliana Top (4702m.) and Capella (3860m.) in the Star Mountains of West Irian. Probably the most striking morphologic feature of this mountain belt is the very steep escarpment which looms above the Fly-Digoel shelf. South of Juliana Top the range front rises at a rate of approximately 4000 meters in thirty kilometers. Farther west in the Carstensz Mountains the scarp rises at a rate of 5000 meters in forty kilometers. The abruptness of this escarpment and the absence of an extensive foothills zone is a unique character of this portion of the New Guinea cordillera.

Central cordilleran region.-- This term is applied to the segment of the cordilleran belt lying between longitudes 143°E. and 146°E. and includes both the Western and Eastern Highlands administrative districts of the Territory of New Guinea. This sector is in many respects morpho-

logically similar to the western cordillera region. It is very high rugged mountain country and again the average elevation is above 2000 meters. The principal mountain ranges include the northwest-trending Bismarck, Kubor and Hagen Ranges. The northern and northwestern end of the region is bordered by the Sepik depression, while the northeastern margin is formed by the Ramu-Markham depression. The major morphologic difference between the western and central cordilleras is that the latter is bounded on the south by an extensive foothills belt which is essentially absent along the southern margin of the western cordillera.

Central foothills region.-- As I have just mentioned the central foothills region of western Papua borders the southern margin of the central cordillera between longitudes 143°E. and 145°E. This zone has been the site of important foreland folding and faulting. Consequently, the morphology of the region is characterized by a typical valley and ridge topography which closely reflects the tectonic character of the region. The elevation of this country ranges from about sea level near the Gulf of Papua to nearly 2000 meters in the interior regions adjacent to the central cordillera. The foothills are drained principally by the Erave-Purari River system and also the Kikori River. Several important extinct volcanoes are scattered throughout the foothills belt but these will be considered separately.

Darai Hills.-- The Darai Hills lie to the southwest of the foothills region between the Kikori and Turama Rivers. In gross aspect they may be considered as part of the foothills but in detail they are clearly a separate morphological unit which can be best described as a highly karsted, limestone plateau. Although the

regional relief is relatively low (maximum elevation ca. 500 m.) the local relief is very rugged owing to the intensive karst development. The limestone plateau is terminated on the northwest by the higher country surrounding Mt. Bosavi, an extinct volcanic peak. The plateau extends 100 kilometers southeastward from that peak to the Gulf of Papua. The southwest margin of the plateau has a scarp-like appearance which is attributed to the flexing of the limestone between the plateau and the lower Fly-Digoel shelf to the south.

Fly-Digoel shelf.-- A vast portion of southwestern Papua and the adjacent regions of West Irian consists of a very extensive (300,000 square kilometers) tract of very low swampy plains which can be regarded as part of the, generally flooded, continental shelf. This region is occupied principally by the meandering courses of Digoel and Fly Rivers, as well as by the Strickland, Bamu and Turama Rivers.

Oriomo Plateau.-- The Fly-Digoel shelf is separated from Torres Strait to the south by a broad, low (maximum elevation ca. 50 m.) west-trending plateau which Carey (1938) has called the Oriomo Plateau.

Kukukuku lobe.-- This term was applied by Carey in 1938 to the rugged, mountainous area which extends southward from the main cordillera and separates the lowlands of the Delta embayment from the Lakekamu embayment to the southeast. The region is drained principally by the Vailala and Tauri Rivers. Like the central foothills region this zone is characterized by very strong foreland-type folding and faulting which is reflected by a well-developed valley and ridge topography. In this case, however, the structural and physiographic grain of the

country has a northerly trend. Elevations range between sea level and about 2000 meters.

Sepik and Ramu-Markham depressions.-- The main New Guinea cordillera is bordered on the north by the Sepik and Ramu-Markham depressions which together form a major crescent-shaped lineament 750 kilometers long. This lineament also separates the main cordillera from the so-called northern ranges; viz., the Bewani, Torricelli, Prince Alexander, Adelbert, Finisterre and Saruwaged Ranges. In general the two segments of the lineaments appear quite similar, but on critical examination some striking contrasts become apparent between the Sepik and Ramu-Markham depressions.

The main morphologic characteristics of the Ramu-Markham depression can be summarized as follows. It is remarkably rectilinear and does not deviate significantly from a northwestward trend for over a distance of 300 kilometers. The depression is quite narrow, seldom greater than 10 kilometers wide, and its margins are regular, well defined and very steep. For instance the southwestern margin of the depression, the so-called Ramu Fall (McMillan and Malone, 1960) drops 2800 meters or more from the crest of the Bismarck Range to the Ramu River in a distance less than 16 kilometers.

In contrast to this, the Sepik depression as well as its western extension, the Meervlakte, in West Irian are both broad marshy plains (50-100 kilometers) and their margins are not nearly so steep nor pronounced as those of the Ramu-Markham depression.

1.1.2 Nature of Quaternary Sediments and Crustal Movements

Extensive accumulations of Quaternary sediments cover the lowlands on either side of the main cordillera in western Papua and New Guinea. The lithologic characteristics of these deposits provides some insight into the nature of Quaternary crustal movements both within the zones of deposition and in the adjacent cordilleran region where uplift and erosion were active. Unfortunately, in the majority of areas it is difficult, if not impossible, to differentiate between Quaternary, particularly Pleistocene, deposits and the underlying Pliocene sediments. In these areas the distinction is made only very arbitrarily or not at all. In the areas immediately adjacent to the highlands belt where Pliocene rocks have been folded it is possible to make a distinction between Pliocene rocks and the overlying, presumably Pleistocene, accumulations with some degree of reliability.

Fly-Digoel shelf.-- The Fly-Digoel shelf is completely blanketed by Quaternary sedimentary accumulations. The most recent deposits are found on the broad alluvial plains adjacent to the many rivers crossing the shelf and in a wide band flanking the western margin of the Gulf of Papua.

The remainder of the shelf is covered by accumulations which are thought to be Pleistocene in age. Along the Kau River in West Irian Bar ^{et al.} (1961) have reported approximately 750 meters of presumably late (?) Plio-Pleistocene deposits (Birim Formation) which overlies unconformably both the Pliocene (?) (Boeroe Formation) and Upper Miocene rocks. The deposits consist predominantly of conglomerates, sandstones, siltstones and shales containing abundant volcanic effusive. The basal units of Birim Formation contain a considerable amount of

volcanic material including very tuffaceous sandstones and lahar-type breccias. An andesitic lava was observed at one locality. Conglomerates are very important in the regions nearest the mountains and were deposited as huge alluvial fans up to 200 meters thick. These alluvial fans attest to a period of vigorous erosion associated with the rapid uplift of the main range. To the south away from the mountains, sedimentation continued in a littoral environment with occasional marine incursions and with the deposition of cross-bedded, tuffaceous sandstones which grade upwards into lignitic siltstones and claystone.

Eastward along the southern flanks of the western cordillera a similar sequence of deposits has been described by G.A.V. Stanley (JE*, 1949) in the Cecilia River area. Still farther eastward the accumulations pass laterally into the agglomerates and associated deposits constituting the volcanic aprons of Mounts Sisa and Bosavi. At the Strickland River and eastward, Stanley also observed a marked unconformity between these rocks, which he assigned to the Pleistocene, and the folded Pliocene rocks beneath.

The Quaternary deposits thin considerably to the south of the peri-mountain belt and fan out across the Fly-Digoel shelf where they consist of clays, sands, siltstones, marls and mudstones, all with a variable volcanic and lignitic element.

The Fly-Digoel shelf is presently thought to be subsiding (Carey, 1938b; Verstappen, 1959) as indicated.

* Code letters of Australasian Petroleum Co. reports. See Selected Bibliography.

by the swampy nature of the interior plains, the flooded coastline and the conspicuous lack of coral reefs. Carey has pointed out that the rate of subsidence has been slow enough for sedimentation to keep the offshore shelf sea shallow and for the deltas to advance but fast enough to keep the numerous anastomosing channels of the deltas open and deep. Pleistocene accumulations on the central part of the Fly-Digoel shelf indicate an environment of deposition very similar to that existing at present. Consequently, if the shelf were indeed sinking, it would be necessary that the average rate of deposition would equal or slightly exceed the post-Würm eustatic rise of sea level (ca. 100 meters). The other alternative is that the shelf was uplifted slightly at a rate approximating that of the rise of sea level. As yet there is too little known about both the age and the thickness of the Quaternary sediments on the Fly-Digoel shelf to provide a conclusive answer to this question.

The Oriomo Plateau represents a neutral block separating the presumably sinking Fly-Digoel shelf from the generally negative Torres Strait zone to the south.

Delta embayment.-- The Delta embayment is the second largest area of Quaternary deposition in western Papua. There the Quaternary is represented by deltaic materials which accumulated at the mouths of the Purari, Era and Kikori Rivers. The Wana bore, which was drilled on the Era River near the center of the embayment, penetrated 16 meters of unconsolidated silty material which was regarded as Recent alluvium. This material was followed by 264 meters of soft, unconsolidated, coarse sandstones and silty mudstones, frequently carbonaceous and with some lignite. These beds were assigned to the Pleistocene and Upper Pliocene.

Like the Fly-Digoel shelf to the west, the Delta embayment appears to have acted as a stable or slightly subsiding platform throughout the Quaternary and served as a receptacle for the detritus removed from the rising foothills zones around its periphery; viz., the central foothills and the Kukukuku lobe.

Western cordilleran region.-- Verstappen's (1960) geomorphic studies in the Star Mountains area represent the extent of our knowledge of morphogenic mountain-building movements in the western cordilleran region. Verstappen describes two main periods of orogenic movement in the late Tertiary and in the Quaternary. From the age and structural relationships of sediments fringing the main ranges, he infers that the mountains were folded and then uplifted near the end of the Pliocene. By the time the youngest Pliocene sediments had been folded, erosion had reduced the new mountain range to moderate relief. Verstappen then postulates a second period of morphogenic uplift which has produced the present mountains.

The great alluvial fans and other piedmont-type deposits of the Birim Formation, which flank the southern margin of the western cordillera, accumulated at that time as a result of the intense action of erosion and denudation accompanying morphogenic uplift. Verstappen interprets the flat-topped nature of the Star Mountains, especially the Mann-Tinne Mountains to the west, to be the uplifted remnants of the erosion surface which developed during the Pliocene.

Verstappen emphasizes the very young morphogenic development of the Star Mountains which he feels is much younger than that of the Alps. It is his impression

that this last morphogenic phase of mountain building did not reach its culmination until after the Riss glacial stage, possibly less than 100,000 years ago. He has formed this conclusion because the glacial deposits in the Star Mountains are thought to belong to the Würm stage, and no traces are found of any earlier glaciation. Presumably, it is his opinion that there were no earlier glaciations because the mountains were not high enough. Verstappen's observations suggest a substantial amount of morphogenic uplift during the pre-Würm Pleistocene, probably in the order of 2-3000 meters in 100,000 to 1,000,000 years. Such a figure is in accordance with the rates of crustal movements as have been revealed by studies in Fennoscandia and elsewhere. It is certainly in accord with the characteristically rapid Pleistocene morphogenic development of other orogenic belts on the Pacific margin, notably in New Zealand.

Although I believe that such wholesale morphogenic uplift of the New Guinea cordillera may have occurred in the late Pleistocene, I must point out that the above line of evidence must be regarded as being very tenuous until it is substantiated by further geomorphic investigations in New Guinea and until a better understanding of the distribution of Würm-Riss glaciations in the entire southwest Pacific region is achieved.

Central cordillera region.-- The central cordillera has had a complex history as a positive region and as shall be seen, it has been tending toward increasing definition since at least the Upper Miocene. Rickwood (1955) has suggested a post-Pliocene episode of folding followed by a period of uplift resulting in the development of the highly dissected highland terrain. The valleys were subsequently filled with thick volcanic accumulations

from the eruption of Mounts Hagen (4070m.) and Giluwe (4270m.). Reiner (1961) has reported one phase of Pleistocene glaciation on Mount Wilhelm (4800m.) in the Bismarck Range. If Verstappen's reasoning concerning glaciation in the Star Mountains is correct and it may be applied to the Bismarck Range, then it appears that the central cordilleran ranges may have also reached their present elevations after the Riss glacial stage. Mount Giluwe and Mount Hagen are also reported to be glaciated (M.J.J.Bik, 1963) indicating that volcanism was pre-Würm. If this latter observation is correct, as well as the assumption that morphogenic uplift culminated in the post-Riss, then at least the final phase of volcanism is restricted to a rather narrow interval possibly corresponding to the Riss-Würm interglacial period.

Central foothills.-- Both tectogenic and morphogenic processes of mountain building were active in the central foothills during the Quarternary. The strongly folded and faulted foreland belt is in part due to early Pleistocene as well as late Pliocene crustal movements. Uplift was probably concurrent with folding and eventually resulted in the development of the valley and ridge topography throughout the folded region. However, uplift proceeded at a considerably slower rate than was apparent in the central cordilleran region to the north, hence, the folded belt lagged behind as foothills.

As in the highlands uplift and denudation were followed by an active phase of Quaternary volcanism. Recently Bik (1963) noted that the volcanic valley fills along the Erave River, which are attributed to Mount Giluwe, have been faulted.

Sepik and Ramu Markham depressions.-- The large number of earthquake epicenters which have been located along the Sepik and Ramu-Markham depressions indicate that they are the most tectonically active zones in New Guinea. These are presumed to be actively sinking zones.

The Sepik River valley is covered by extensive swampy alluvial deposits which overlie Pleistocene gravels, sands and silts of terrestrial, estuarine and even marine origin. These deposits are probably quite thick along the axis of the depression. The Ramu and Markham Valleys are choked with alluvial and piedmont deposits which are also assumed to be very thick.

1.1.3 Volcanism

Sixteen extinct Quaternary volcanic centers and one dormant center, ranging in elevation from less than 100 to 4088 meters, are scattered over a roughly trapezoidal area of western Papua and the adjacent parts of New Guinea (Figure 1 and Plate 1). These volcanoes are outstanding features both from the standpoints of Quaternary morphogenesis and of the overall development of the New Guinea cordillera.

The form and composition of the volcanoes attest to a period of strong, explosive volcanism. In general, the volcanoes are the normal composite type (stratovolcanoes) and consist predominantly of the Pacific suite of extrusive rocks including olivine basalts and agglomerates which usually grade upward into and are intercalated with andesitic lavas, tuffs and agglomerates.

The volcanics accumulated on a highly dissected surface of folded and faulted Pliocene and older strata.

With the exception of Yelia in the headwaters of the Tauri River (lat. 7°S. , long. 146°E.) there is no record of activity in historic times. Despite the severe conditions of tropical erosion most of the cones are rather well preserved. Mount Hagen and Mount Giluwe are reported to have been glaciated (M.J.J.Bik, 1963) probably during the Würm stage. In the light of these observations it is concluded that the majority of the volcanoes were active during the latest Pleistocene or even the early Recent.

Ten of the seventeen Quaternary volcanoes form a 350 km. linear zone which extends eastward from Mt.Sisa to Mt. Yelia. The belt includes Mounts Rentoul, Sisa, Kerewa, Giluwe, Ialibu, Suaru, Karimui, Yelia and Crater Mountain. It is important to observe that this zone also marks the boundary between the central cordillera and the foothills to the south. To the west beyond Mt.Sisa the volcanic lineament is contiguous with the steep, scarp-like southern flank of the western cordillera. The tectonic significance of this feature will be considered in a later section.

1.2 PLIOCENE DIASTROPHISM

1.2.1 Pliocene Rocks

The nature and distribution of Pliocene rocks attests to a period of active mountain building with both important tectogenic and morphogenic movements. The Pliocene rocks accumulated in two elongate troughs which were marginal to the southern flanks of the rising cordillera (Fig.1 and Plate 1). The westernmost trough is located in the headwaters region of the Fly and Strickland Rivers and contains a very thick sequence of predominantly clastic continental and transitional sediments with an important element of volcanic material. These rocks thin considerably to the south and are spread over a vast area of the Fly-Digoel shelf where they were also deposited mainly in a continental and transitional environment.

The eastern trough is developed in the Purari River - Delta embayment region. The sediments are dominantly clastic but unlike the Pliocene rocks to the west they were deposited mainly in a marine environment. There is also considerably less volcanic material associated with the sediments. The Pliocene accumulations are folded in both these areas which indicates a phase of late Pliocene to early Pleistocene tectogenesis.

Digoel-Strickland basin.-- This term is used mainly in the sedimentary sense and to a lesser extent in a structural

PLIOCENE ISOPACHS AND LITHOFACIES

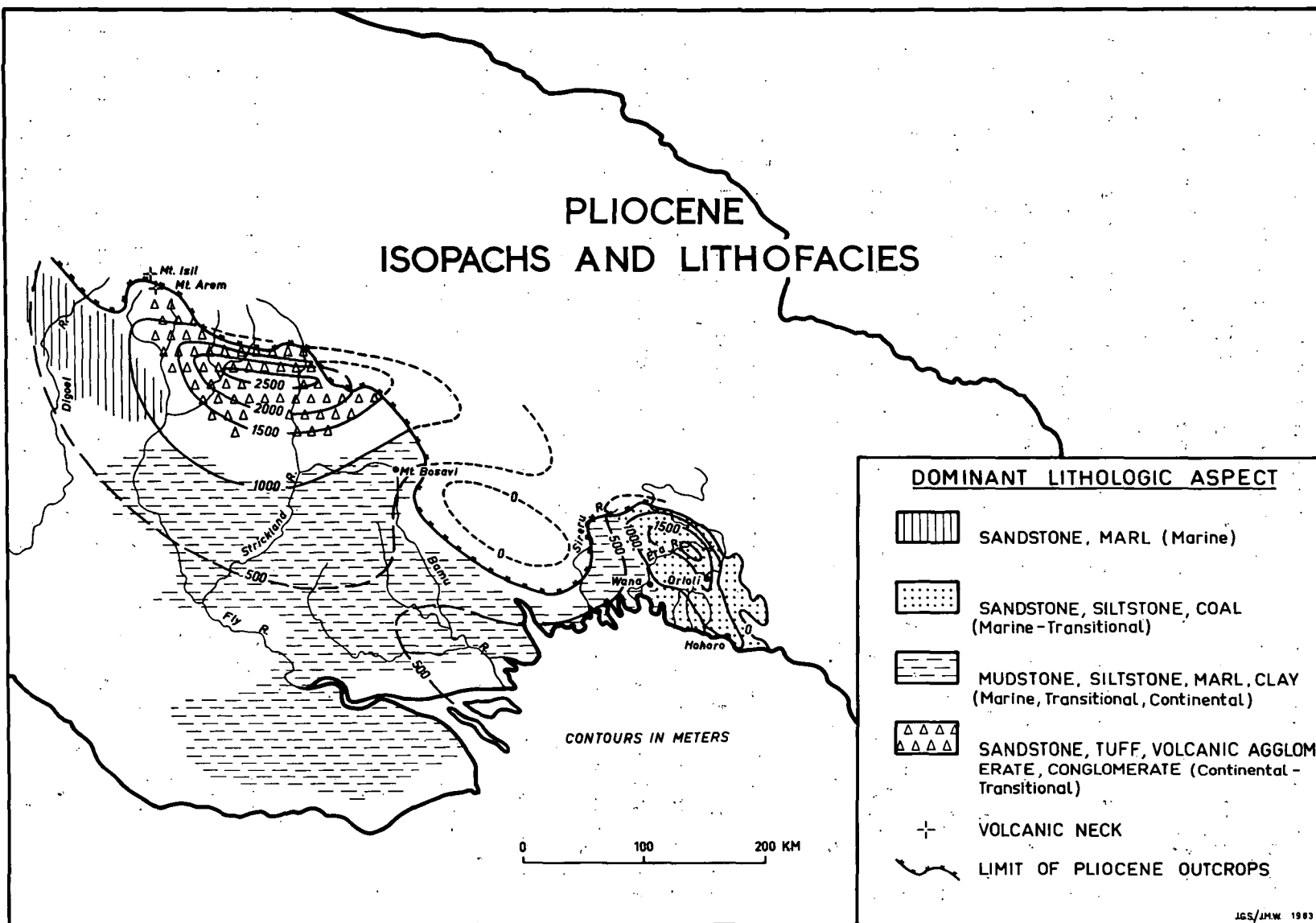


Figure 2

sense to denote the trough-like accumulation of Pliocene rocks which parallels the southern margin of the western cordilleran region from the Digoel River in West Irian eastward to Mount Bosavi in Papua. In the low to moderately hilly country south of the Star Mountains region the Pliocene rocks are represented by the Boeroe Formation. The exact age of this unit is doubtful and it is possible that some of the upper beds may be Pleistocene. Groot (1940) assigned the Boeroe to the Late Pliocene, whereas Hermes and Schumacher (1957) represented the Boeroe Formation as belonging to the Tertiary "g-h" Stages. Finally Bär et al. (1961, Fig. 10) placed the Boeroe Formation in the early Plio-Pleistocene.

In the East Digoel River area the Boeroe Formation consists of two units of marine sediments. The lower unit consists of sandy marls and calcareous sandstones with subordinate shales and siltstones. This sequence is overlain by calcareous silty or sandy shales and siltstones. Ostracoda and shell fossil beds, lignite streaks and plant remains are quite common in the upper unit. The thickness of the Boeroe Formation is estimated at 600 meters along the East Digoel River.

East of the Kau River the Boeroe Formation is apparently overlapped by the terrigenous rocks of the Pleistocene (?) Birim Formation. Bär indicates that the normally marine Boeroe Formation may be represented in part by volcanic, terrigenous sediments in this region. The upper part of the Boeroe Formation may be equivalent to the Birim Formation. Certainly in the adjacent parts of Papua the Pliocene is represented by thick non-marine, tuffaceous sediments. In the Ok Tedi area for instance the Pliocene consists of non-marine, tuffaceous sandstones and tuffs with bands of conglomerate and volcanic

agglomerate. In the Strickland River area G.A.V. Stanley (JE,1949) reported up to 2500 meters of Pliocene rocks, the Strickland Formation. These consist chiefly of a non-marine, well-bedded sequence of alternating conglomerates, tuffaceous sandstones, silts and mudstones, all containing a great deal of lignitic material and with only a few occurrences of microfossils.

The eastward passage from a marine to a non-marine tuffaceous facies was probably due to the presence of several volcanic centers in the rising highland zone adjacent to the eastern end of the Digoel-Strickland basin which were absent to the west.

Immediately south of the Fly-Strickland headwaters region the Pliocene rocks are overlapped by extensive Pleistocene deposits leaving a wide gap in the information between the outcrop belt and subsurface information available to the south. R.L.Bullock (WB, 1939) reported that the gravity values southwest of the Cecilia anticline indicate the presence of a major synclinal structure containing sediments possibly up to 3000 meters thick and probably of Plio-Pleistocene age.

Fly-Digoel shelf.-- Throughout the Fly-Digoel shelf the Pliocene ranges in thickness between 0 and 300 meters but reaches 450 meters near the mouth of the Bamu River. The rocks in general represent a continental (swamp) to transitional and possibly marine sequence and consist of micaceous and carbonaceous mudstones, siltstones, silty marls and clays all with a variable volcanic element. In the course of the Kaim Survey S.V.Sykes (JH,1953) reported several fine agglomerate beds which he interprets as ash showers, thus providing additional evidence of the

presence of active volcanism during the Pliocene.

Purari basin.-- A relatively thick section (2000-2500 meters) of Pliocene rocks is developed in the Purari basin which is located in the foothills bordering the north-eastern rim of the Delta embayment. These rocks are in many respects similar to those occurring in the Digoel-Strickland basin. However, a larger proportion of Purari basin rocks, especially the lower part, was deposited in a marine environment and the derived volcanic content of these rocks appears to be considerably less than that of the Digoel-Strickland basin.

Probably the most representative occurrence of Pliocene rocks in the Delta region is that exposed along the Era River. There the Pliocene consists of three main units which total approximately 2000 meters. The stratigraphic sequence in descending order is as follows: (1) a unit 500 meters thick consisting of massive tuffaceous sandstone which passes downward into carbonaceous mudstones, then finally into massive cross-bedded sandstone; (2) a mudstone-sandstone sequence with many seams and lenses of low rank to sub-bituminous coal (550m.); (3) the basal unit in this section is 800 meters thick and is composed of well-compacted marine sandstone, siltstone and mudstone, all with a calcareous cement.

Elsewhere in the Delta region and in the adjacent areas the Pliocene is mostly represented by partial sections of the lithologic assemblages described in the Era region. However, there are some variations worthy of note. At Kuru for instance the Pliocene is represented by 250 meters of mudstone and siltstone grading downward into strongly cross-bedded sandstone, and finally underlain by a basal conglomerate unit 15 meters thick. The

conglomerate contains pebbles and cobbles of quartz, chert, acid plutonic rocks and some metamorphic types.

Following deposition these rocks were folded and differentially eroded. Consequently, the Pliocene outcrops in the Delta region are rather scattered making a completely reliable reconstruction of the original extent of the Pliocene accumulations difficult.

In general the Purari basin has an arcuate form and extends from the gulf coast near Hohoro northward for about 60 kilometers then swings westward into the middle Purari River area paralleling the northern edge of the Delta embayment. It appears that the zone of maximum deposition coincides with the homoclinal rim of the embayment. Thicknesses along this zone range from 2000 meters along the Era River to nearly 2500 meters in the Hohoro-Orloli area. To the north the Pliocene thinned to at least 600 meters as shown by exposures on the northern edge of the Pide basin where it is cut by the Purari River. The Pliocene also thinned southwestward away from the axis to nearly 950 meters at Wana on the Era River.

The relations along the westernmost margin of the basin are obscure. Here it is rather critical to the reconstruction of Pliocene paleogeography to know whether the western edge of the present outcrops corresponds to a former shore line zone or is a tilted and eroded edge. The information available, particularly in the Kuru-Sireru area, suggests that the Pliocene rocks did thin to the west and the extent of outcrop may in fact be an approximation of the original western margin of the Purari basin. The inferred configuration of both the Purari and Digoel-Strickland basins is

illustrated in Figure 2.

1.2.2 Framework of Pliocene Diastrophism

Digoel-Strickland basin.-- The nature of the Pliocene rocks exposed in the Digoel-Strickland basin attests to a period of considerable tectonic unrest. Like the mplassé facies of the Alps the terrigenous conglomerates and sandstones which accumulated in this basin are most likely to have been associated with the morphogenic phases of mountain building.

The location and configuration of the basin as well as the nature of its sediments indicate that it formed as a marginal trough or exogeosyncline (Kay, 1951) which paralleled a rapidly rising cordilleran zone to the north (Fig. 3). This orogenic movement was accompanied by an active episode of volcanism which is evidenced by the high content of derived volcanic materials in the sediments. As I have pointed out volcanism was apparently most intense along the eastern end of the basin because to the west the Boeroe Formation is dominantly marine with little, if any, derived volcanic material. Such a locus of volcanic activity in the hinterland explains both the high volcanic content and the terrigenous nature of the Pliocene in the Fly-Strickland headwaters region, since the volcanic terrain was undoubtedly eroded very rapidly and the sediments accumulated in the marginal trough at a rate exceeding that of subsidence. Two volcanic plugs (Mt. Isil and Mt. Arem) have been reported by Bär on the southern flanks of the main ranges near longitude 141°E. (Fig. 2). These are presumably remnants of volcanic centers which were outliers of the main volcanic focus. The main focus was probably located farther to the north and east and was most likely removed

PLIOCENE DIASTROPHIC FRAMEWORK

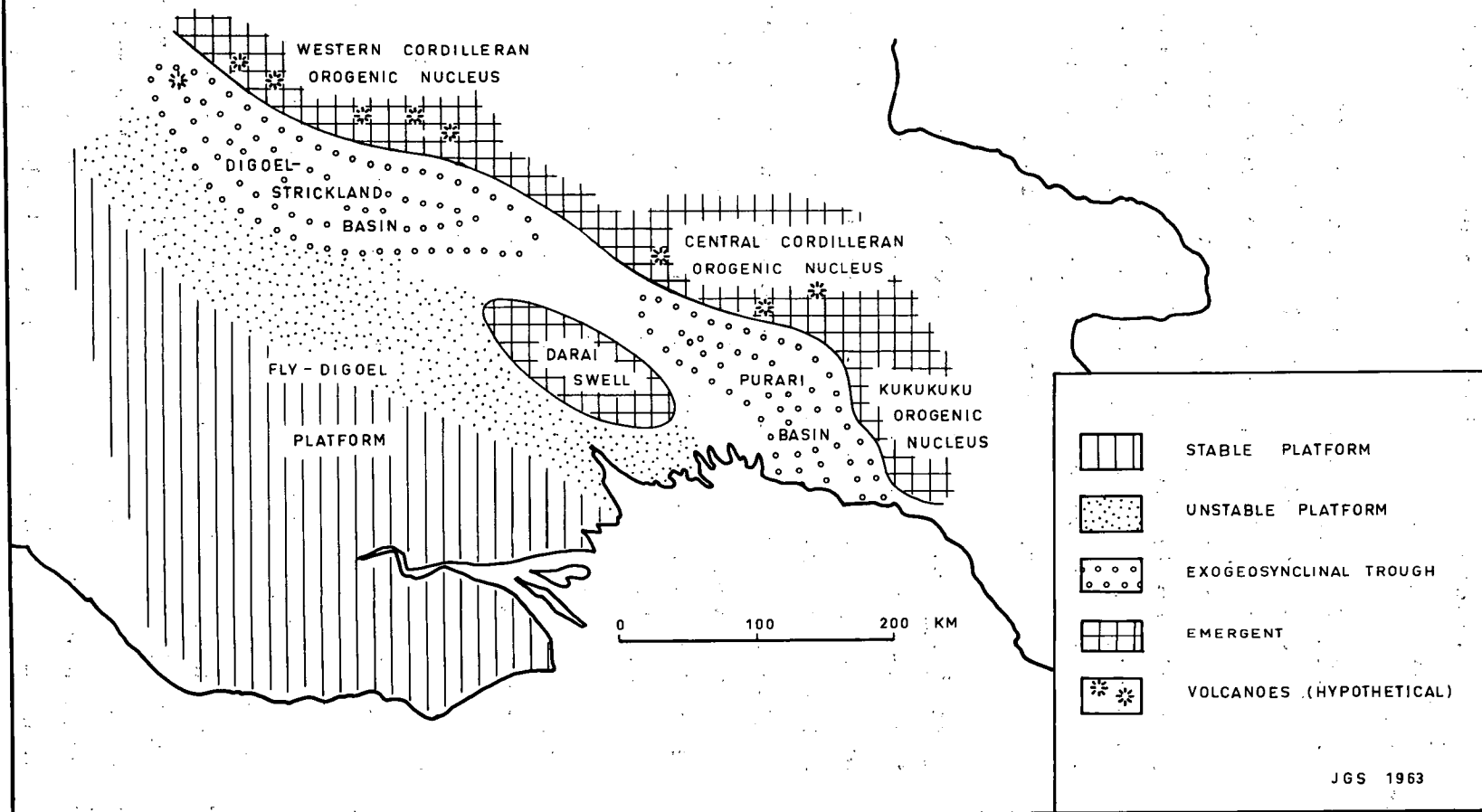


Figure 3

by the intensive period of Quaternary uplift and erosion in that region.

Fly-Digoel platform.-- The micaceous and carbonaceous mudstones, siltstones, silty marls and clays which have a thin but continuous development across the Fly-Digoel shelf are typical of a stable or mildly unstable platform tectonic environment. The depositional environment was probably much like the present day conditions, i.e., dominantly continental (swamp) and transitional (deltaic) but with occasional marine incursions.

Purari basin.-- Like in the Digoel-Strickland basin to the west the Pliocene sediments in the Purari basin have been deposited in a trough marginal to a tectonically active land mass lying to the north. In contrast to the Digoel-Strickland basin volcanism was not as active in the source area, at least not in the earliest Pliocene. At that time marine conditions prevailed in the Purari trough. However, as the rate of uplift increased, sedimentation in the marginal exogeosyncline eventually exceeded subsidence and marine conditions retreated from the area. Apparently this more active phase of tectonism to the north was accompanied by some volcanism as is evidenced by the presence of a tuffaceous element in the non-marine Pliocene rocks in the Purari basin.

The rather anomalous occurrence of plutonic pebbles and cobbles in the basal Pliocene at Kuru probably are the result of rapid uplift and denudation in the central cordillera where such rocks are exposed. They were probably carried along by a rather swift river system with a course similar to that of the Erave and were deposited in a deltaic environment which existed in the Kuru region during the Pliocene.

Continuity of the Pliocene exogeosyncline.-- In light of the present information it appears that the Pliocene deposition occurred in two elongate, oval basins which were marginal to an actively rising orogenic front roughly paralleling the present cordillera. These basins are separated by a strip approximately 260 kilometers long in the Kikori River area (Fig.2) where Pliocene rocks are now absent. The problem is whether or not these basinal nodes developed separately or once extended as a continuous exogeosynclinal belt through the upper Kikori area. It is rather certain that Pliocene deposition in both basins, especially the Digoel-Strickland basin, did extend beyond the present limits of outcrop (Fig.2). However, it is doubtful whether any Pliocene accumulations in this intervening strip reached the thicknesses displayed in the adjacent basins. If thick Pliocene deposits did exist in the Kikori-Erave area, it would mean that a substantial amount of post-Pliocene uplift and denudation would have been necessary to remove these rocks. Such a situation is certainly possible, but I would rather attribute the absence of the Pliocene rocks in this region to the presumption that the accumulations were quite thin in contrast to the adjacent basins or non-existent.

Thus on the basis of this assumption, it can be seen that maximum sinking and deposition along the exogeosynclinal belt was concentrated in two regions; viz., the Digoel-Strickland and Purari basins. This pattern could be interpreted to mean that the uplift of the main cordillera was not uniform and the most intense movement was concentrated in the regions situated to the north of the main Pliocene basins. These regions correspond to the hearts of the present western and central cordilleran regions where the extensive exposures of Mesozoic sedi-

ments and older crystalline rocks attest to the vigorous nature of Pliocene uplift. These regions will be referred to as the central and western cordilleran orogenic nuclei (Fig.3).

It should be noted that the Kukukuku lobe was also the locus of quite strong uplift at that time and was the source of the thick clastic deposits which accumulated along the eastern margin of the Purari basin.

Darai swell.-- The Darai Hills are situated in a zone which during the Pliocene represented a hinge between the actively sinking exogeosynclinal troughs and the Fly-Digoel platform. There are at present no Pliocene sediments in the Darai area, but it is not certain whether this absence is due to nondeposition or to subsequent Quaternary erosion. However, as will be shown, the area was emergent during the Upper Miocene and it is thought that such positive movements may have persisted into the Pliocene.

If the so-called Darai swell did exist in the Pliocene, its relief was quite low since the sediments around its periphery are all predominantly mudstones which do not attest to rapid erosion of a strongly uplifted zone. The Pliocene paleogeography of the Darai swell may have been very much like that of the present Aru Islands in the Arafura Sea off the south coast of West Irian; i.e., a low upwarped island surrounded by shallow shelf seas.

1.2.3 Chronology of Pliocene and Quaternary Movements

In the previous sections I have shown that both the Quaternary and Pliocene epochs were characterized by

intense morphogenic uplift. Since I have also suggested that uplift is frequently associated with tectogenesis (i.e., folding and faulting), it is necessary to briefly examine the chronologic relationship of these phenomena before proceeding to a discussion of Upper Miocene diastrophism. The structural characteristics and mechanisms of folding, however, will be examined in a later section.

From a chronological point of view there are two types of folding developed in western Papua and New Guinea. The first and most basic type of folding has been of a secular nature and its development extended over a span of several epochs. The folds are quite large and represent the basic anticlinoral framework of the main cordillera which is in turn reflected in the external morphology of the cordillera. Because of this relationship, I will make no distinction between primary folding (primary tectogenesis) and morphogenesis in the course of this discussion.

In contrast the development of the second type of folding, mainly represented by the central foothills folded belt, was episodic; the individual structures are much smaller and the relationship with morphogenic uplift was purely secondary. Hence, these latter folding movements will be spoken of as secondary tectogenesis. The following pages are devoted mainly to the consideration of these secondary folding movements.

Central foothills.-- Geologists working in the foothills of central Papua in the early 1900s in the search of oil, coal and other mineral resources were able to unravel enough of the Tertiary stratigraphy to realize that Pliocene rocks were deformed along with the older Tertiary

sediments. E.R. Stanley (1923) in his pioneering paper, The Geology of Papua, stated that ". . . throughout the littoral of New Guinea there is evidence of some stupendous earth movements during the late Tertiary times commencing probably in late Miocene and reaching a maximum in the Pliocene or early Pleistocene." Subsequent extensive studies, largely conducted by petroleum exploration companies, have not substantially altered this view, and it was concluded by the Australasian Petroleum Company (1961) that ". . . most of the deformation occurred during a single orogenic phase at about the end of the Pliocene." Perhaps this could be stated more accurately in the form: about the end of Pliocene sedimentation in Papua, because it has never been established whether or not a complete Pliocene section is present in Papua. For instance, it is possible that deformation occurred in the late Pliocene after the deposition of the early Pliocene rocks. However, if the entire Pliocene is present in Papua it would mean that a large part of the folding was mostly early Pleistocene. Recent movement is indicated by Bik's (1963) suggestion that Pleistocene volcanic valley-fills along the Erave River are faulted.

The lower age limit of folding is equally difficult to establish. E.R. Stanley stated that the deformation began in the late Miocene. Carey (LI, 1941) in a report on the Purari River region found the thickness and facies variations of the Pliocene rocks to show no relation to the structure. Consequently, he concluded that ". . . although some of the folds show considerable nascent activity dating back probably as far as early Muruan (Upper Miocene) times these uplifts were for the most part planed off in the early Pliocene and the main folding did not occur until after the Pliocene." I have found

no reason to disagree with Carey's conclusion for the Purari River region. However, A.Kugler, my colleague who has been concerned with the tectonics of the Kukukuku lobe, believes that there is some indication that folding movements were in progress during the deposition of the Pliocene sediments and possibly during the Upper Miocene as well. Thus, one can only conclude that the main phase of secondary folding in the central foothills of western Papua occurred during the late Pliocene and/or the Pleistocene. Allowance must be made, of course, for regional variations in both the age and intensity of folding ranging from incipient stages as old as Upper Miocene in the Kukukuku lobe to Recent movements in the Erave River region.

We can now summarize the sequence of Plio-Pleistocene orogenic events in the central cordillera and central foothills as follows:

1. Uplift, denudation and erosion of the central cordilleran orogenic nucleus and complimentary sinking of the adjacent Purari exogeosynclinal basin. Pliocene.
2. Folding of the Pliocene and older beds in the central foothills. Plio-Pleistocene.
3. Continued uplift of the central cordillera. Volcanism in the central foothills and along the southern margin of the central cordillera. Quaternary.

Western cordillera.-- The chronology of mountain building movements in the western cordilleran region is essentially the same as that of the central cordillera and the folded foothills belt. However, the unconformity

between the folded Pliocene and presumably Pleistocene beds indicates that at least secondary folding had died out before the end of the Pleistocene. The sequence of movement is as follows:

1. Volcanism and morphogenic uplift of the western cordilleran orogenic nucleus and molasse-type deposition in the Digoel-Strickland basin. Pliocene.

2. Folding of the Pliocene exogeosyncline possibly followed by the development of an extensive erosion surface. Late Pliocene or early Pleistocene.

3. Substantial morphogenic uplift in the late (post-Riss) Pleistocene culminating in the present relief and the formation of the extensive piedmont deposits flanking the southern margins of the western cordillera.

1.3 UPPER MIOCENE DIASTROPHISM

Upper Miocene rocks have a widespread distribution throughout westernmost Papua in the regions south of the main cordillera. The Upper Miocene term is applied to a succession of Tertiary rocks which corresponds to the Muruan Stage in the local nomenclature worked out by M. F. Glaessner for the Tertiary of Papua on the basis of the microfaunal succession. This stage is equivalent to the East Indian "g" Stage of van der Vlerk and Umbgrove (1927). The recent work of F. E. Eames et al. (1961) concerning the world-wide correlation of the Miocene has made it possible to apply the nomenclature of the European Miocene to Papua. According to them the Muruan or "g" Stage is equivalent to the Upper Miocene.

1.3.1 Upper Miocene Rocks

As can be seen from the isopach and lithofacies map (Fig. 4) the Upper Miocene rocks can be separated into two main facies divisions on the basis of the dominant lithologic aspect; viz., a limestone facies occurring on the Fly-Digoel shelf and a mudstone facies belt developed principally in the central foothills region. These two main facies will be dealt with separately.

Limestone facies.-- Limestone is the dominant lithological aspect of the Upper Miocene rocks present on the Fly-Digoel shelf and in the headwaters region of the Fly

UPPER MIOCENE ISOPACHS AND LITHOFACIES

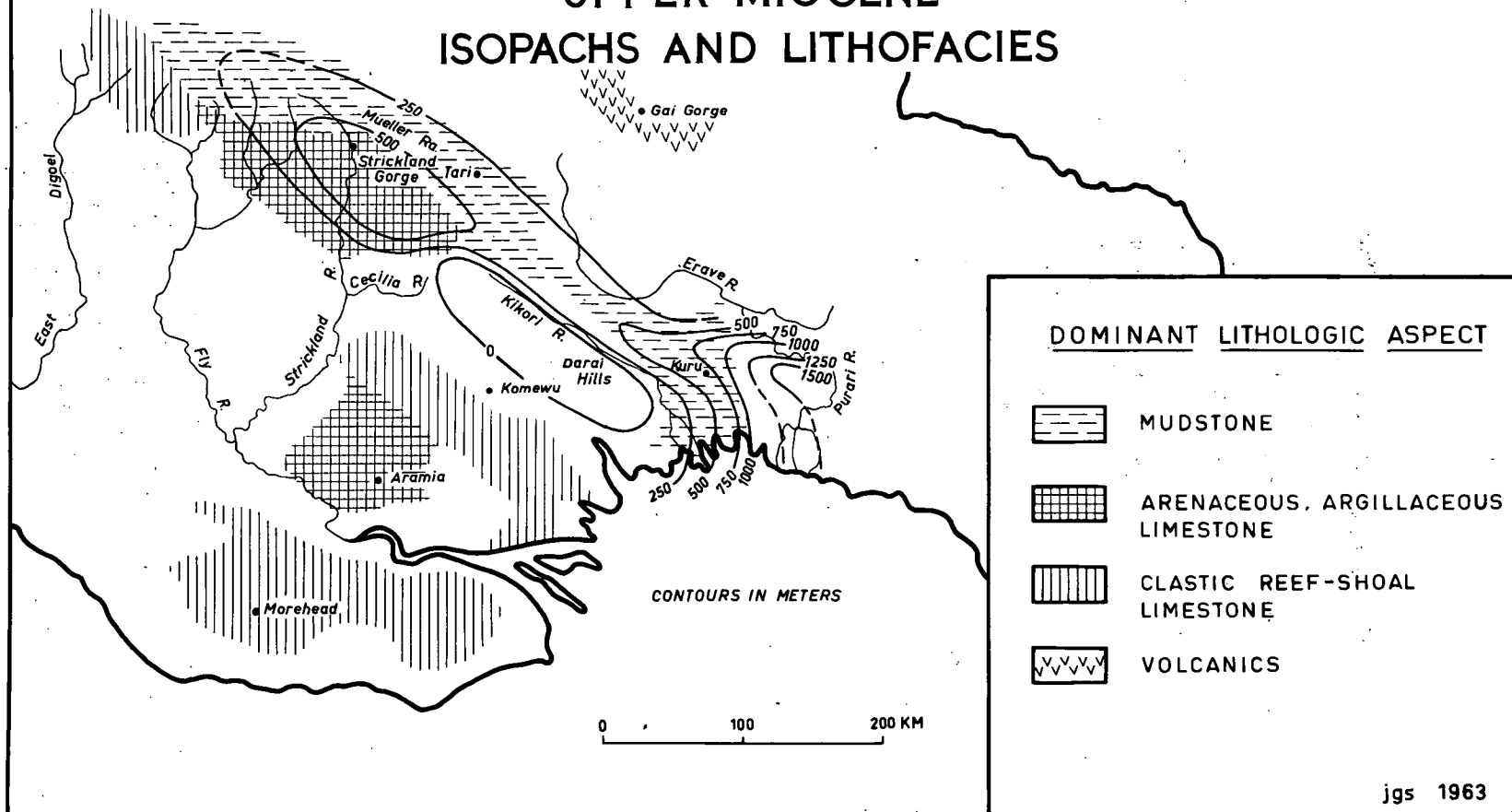


Figure 4

jgs 1963

and Strickland Rivers. The rocks occurring in these regions are referred to as the Upper Miocene limestone facies. It is possible to recognize two subunits in the limestone facies on the basis of the argillaceous and arenaceous content of the rocks: an argillaceous and arenaceous limestone subfacies which is developed mainly in the Fly-Strickland headwaters region and a nearly pure, calcareous subfacies which is found in the Fly-Digoel shelf region and in the Star Mountains region of West Irian.

A large area of the Upper Miocene development on the Fly-Digoel shelf is composed of shoal and littoral-type limestone and shows an outstanding lack of argillaceous or arenaceous land-derived materials. The sections recorded in the Morehead and Komewu No.2 bores are typical of this subfacies. At Morehead a section 270 meters thick composed of clean white, medium to coarse-grained, shoal-type detrital limestone was assigned to the Upper and Middle Miocene. It is impossible to estimate what portion of this section is restricted to the Upper Miocene. The foraminifera Alveolinella quoyi and Marginopora sp. occurred at two main horizons. At Komewu a section 370 meters thick of a generally similar lithology, but again lacking any diagnostic fossils, was assigned to the Upper and Middle Miocene on the basis of its stratigraphic position. The rocks are composed of porous, shelly detrital limestone and recrystallized algal detrital limestone.

A limestone sequence, lithologically very similar to the Upper Miocene and Middle Miocene occurrences at Morehead and at Komewu No.2, has been described by Bär (1961) in the Star Mountains region of West Irian. According to him these rocks consist of massive to thick-

bedded, gray to light gray, slightly sandy calcarenites in which reef-type limestones occur locally (corals and algae in patch reef or biostromal development). Intercalations of yellow-white chalky limestones were found but terrigenous layers, if present, are of minor importance. The thickness varies from 180 to 250 meters in the Iwoer-Denom River area. The rocks are dated by a pelagic foraminiferal assemblage which indicates that their age ranges from late Miocene up to the earliest Plio-Pleistocene. Bär tentatively placed these rocks, the so-called Kau Limestones, at the base of the Plio-Pleistocene. However, in order to be consistent with the usage in existence throughout Papua, I prefer to emphasize the late Miocene affinities of the Kau Limestones. The lithology, thickness and fauna, including frequent Alveolinella quoyi, are certainly similar to the limestone facies developed on the Fly-Digoel shelf. For these reasons the Kau Limestones will be referred to as being Upper Miocene although, as at Morehead and Komewu, they may also have some Middle Miocene affinities.

The arenaceous, argillaceous limestone subfacies occurs principally in the headwaters region of the Fly and Strickland Rivers but has also been found in the Aramia bore on the Fly Digoel shelf. The Upper Miocene sequence at Aramia is characterized by 105 meters of highly argillaceous limestone, marl, and mudstones containing Alveolinella quoyi and Marginopora vertbralis. This unit is overlain by a section 16 meters thick of silty mudstone and marl which represents an Upper Miocene to Pliocene transition zone. It contains abundant remains of mollusca, bryozoans, echinoids, ostracoda and foraminifera.

To the north near the headwaters of the Strickland

River this limestone subfacies has a significantly thicker development and the argillaceous-arenaceous element is more pronounced. Near the southern exit of the Strickland Gorge the bulk of the Upper Miocene (470 meters) is composed of a white, fine-grained chalky limestone overlain by 120 meters of thin-bedded marine mudstones and gray calcareous siltstones with some coal. In the Cecilia anticline a section (400+ m.) of Upper Miocene rocks is present of which 250 meters are sandy marine beds with intercalations of highly fossiliferous, tuffaceous limestone. The remainder of the Upper Miocene section (160 meters) is composed of a light to dark "cream" limestone. A similar limestone 620 meters thick has been found in the Pari anticline to the west.

Mudstone facies.-- Argillaceous deposits described in the Tari region near the eastern end of the Mueller Range in the western cordilleran region are the westernmost extension of a narrow (ca. 50 km.) belt of Upper Miocene mudstones and associated silts and sandstones that trends northwestward across Papua between the Hegigio or Kikori River on the south and the Erave River on the north. At about long. 144°E. the mudstone belt begins to flare out and widens eastward into a large area of mudstone development which extends southward to the coast and grades into much thicker mudstones, sandstones, conglomerates and graywackes in the Kukukuku lobe east of the Purari River.

Throughout the central foothills region the Upper Miocene, which is represented by partial sections in fault slices and synclines, consists of blue-gray mudstones, usually less than 300 meters in thickness. An important aspect of the so-called soft, argillaceous deposits in the Tari area is the presence of a derived

Cretaceous and Lower Miocene foraminiferal assemblage. The Cretaceous (Cenomanian) forms include: Gumbelina globulosa, Rotalipora cf. appenninica and Globotruncana spp. Forms apparently derived from the Lower Miocene include: Lepidocylinina spp., Cycloclypeus spp., Anomalina spp. and Operculina spp.

As stated, the Upper Miocene increases eastward both in areal extent and thickness and includes more clastic material that is typical of the Upper Miocene development in the Kukukuku lobe. The Upper Miocene rocks described from the Wana well are typical of the mudstone facies. The section, which is 1100 meters thick, is comprised of mudstones, siltstones and sandstone. In the Puri anticline area the sandstones are especially important and units up to 30 meters thick have been described. In the Puri region the Muruan rocks thicken eastward from 1500 to 2000 meters in only a few kilometers.

1.3.2 Framework of Upper Miocene Diastrophism

Fly-Digoel platform.-- The gross composition, texture and thickness of the limestone facies developed over much of the Fly-Digoel shelf indicates that during the Upper Miocene the region had the tectonic character of a platform. A large portion of the limestone facies is composed of relatively thin, fossiliferous fragmental limestone which indicates, according to the criteria of Dapples, Krumbein and Sloss (1948), a depositional environment on a stable platform, possibly slowly subsiding. I have shown the probable distribution of the stable platform tectonic regime on Figure 5.

UPPER MIOCENE DIASTROPHIC FRAMEWORK

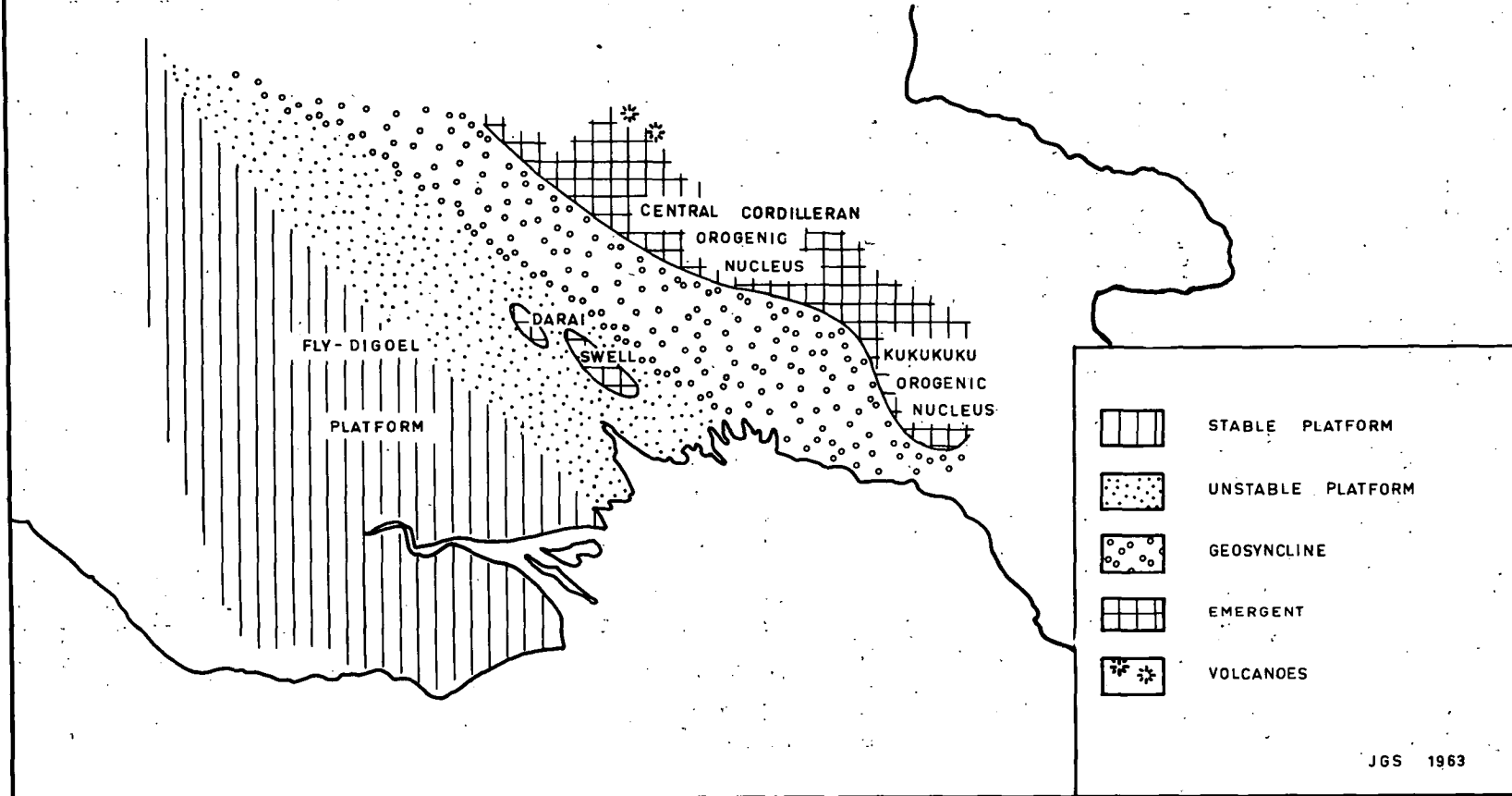


Figure 5

Darai swell.-- As shown in Figure 4 there are no Upper Miocene rocks in the Darai Hills. The problem at hand is to interpret the tectonic significance of the zero isopachs. The first alternative is that the Darai area was emergent in the Upper Miocene and no sediments were deposited. The second possibility is that such deposits may have existed but were subsequently eroded. J.O. Zehnder (KIA,n.d.) has reported a thin detrital limestone in the basal units of the Upper Miocene mudstones on the Iehi anticline which is located along the northern margin of the Darai area. He considered these limestones to have been derived from the Middle and Lower Miocene limestones occurring in the Darai area. This, of course, suggests that the Darai swell may have been an actively eroding positive tectonic unit in the Upper Miocene.

Geosynclinal belt.-- The present areal extent, lithologic character and particularly the general thickness of the Upper Miocene mudstone facies, although attesting to considerable crustal instability, are not strictly typical of geosynclinal deposits. However, it must be remembered that some of these deposits may have been eroded in the Pliocene and Quaternary phases of uplift and it is possible that the belt of Upper Miocene clastic accumulation did reach geosynclinal proportions. This latter situation has also produced a paucity of information which adds to the difficulty of producing a reliable reconstruction of the Upper Miocene "geosynclinal" belt.

I have already described the Pliocene areas of accumulation as exogeosynclinal basins which were marginal to a rising hinterland zone. With this fact in mind it may be possible to explain the nature of the Upper Miocene mudstone belt as representing a transition from orthogeo-

synclinal conditions, which as we shall see were widespread in the earlier Miocene, to the Pliocene exogeosynclinal conditions. In the Strickland headwaters area the Upper Miocene mudstones and marly limestones pass gradually and without break upward into the non-marine Pliocene deposits. The derived Cretaceous and Lower Miocene foraminifera in the Upper Miocene rocks at Tari indicate that uplift and erosion was already active to the north of this area. Such regions of movement may well have been the forerunners of the orogenic nuclei which bordered the Pliocene exogeosynclinal basins. Rickwood (1955) has reported from the Gai Gorge in the central cordillera a sequence of tuffs and volcanic agglomerate which overlies fossiliferous Middle Miocene rocks. These rocks he assigned to the Upper Miocene, thus suggesting the possibility that there may have been some volcanism associated with the rise of the incipient orogenic nuclei. The inferred position of this rising zone is tentatively outlined on Figure 5. Only the central cordilleran nucleus is shown at this stage because the development of the platform-type limestone facies in the Star Mountains region suggests that uplift had not yet begun in that area.

East of the Purari River in the Kukukuku lobe the Upper Miocene thickens considerably and reaches true geosynclinal proportions. There is also an important increase in coarse clastic materials. The thickening was accomplished by the development of an early Upper Miocene mudstone unit which is not present in western Papua. Also, in this region the trend of the main trough of accumulation is nearly north-south rather than northwest as in western Papua. The Pliocene Purari

basin also showed much the same configuration. It is likely that these thick, coarse sediments were deposited as a "clastic wedge" about an actively rising mass in the interior of the Kukukuku lobe. For my purposes, I will refer to this rising mass as the Kukukuku orogenic nucleus.

1.4 MIDDLE MIOCENE DIASTROPHISM

1.4.1 Middle Miocene Rocks

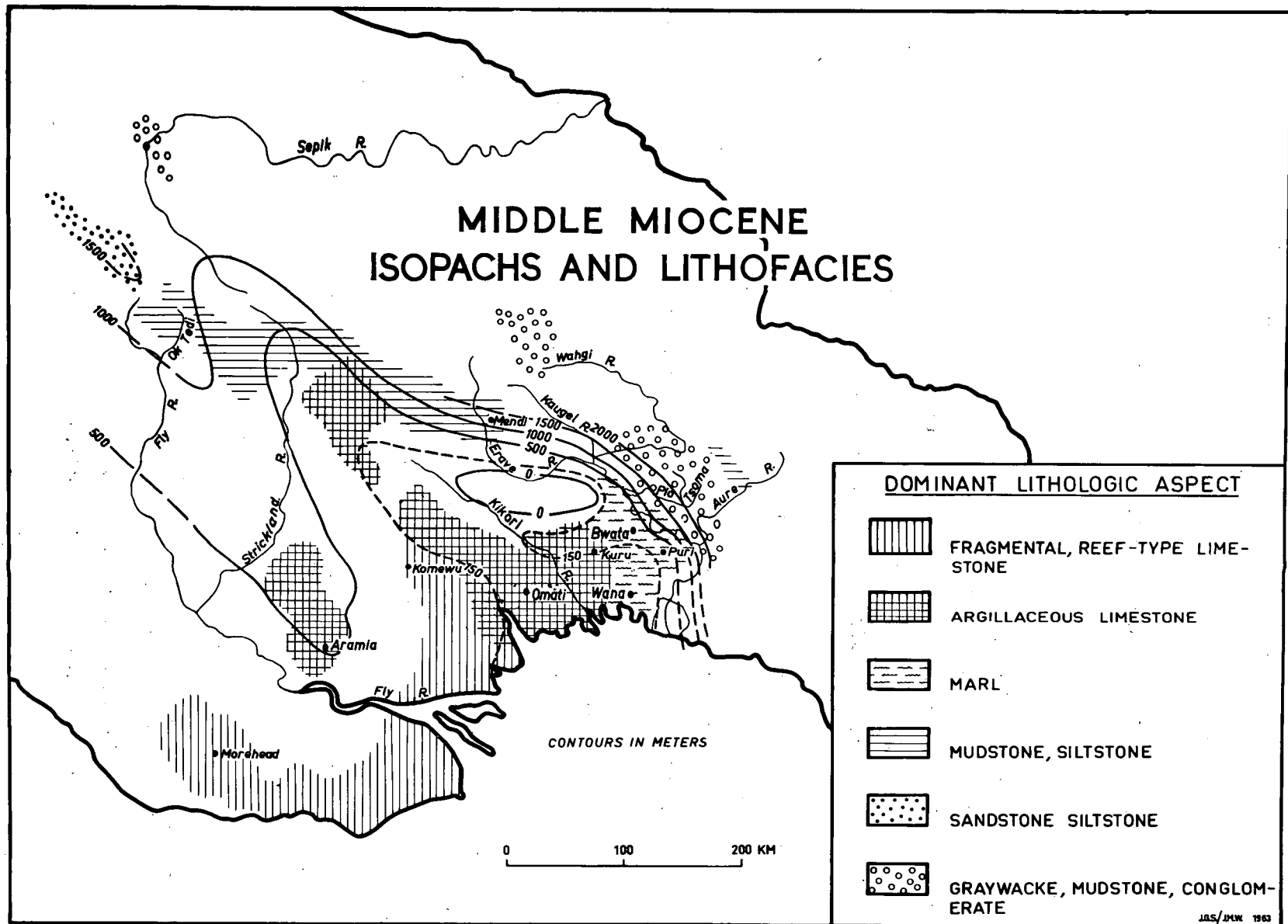
F.E.Eames et al. (1961) have shown that the Middle Miocene nomenclature of the European Tertiary can be applied to rocks in Papua which represent the Ivorian Stage of Glaessner and are equivalent to the "f₃" Stage in the East Indian terminology of van der Vlerk.

On the basis of their dominant lithologic aspect, the Middle Miocene rocks of Papua can be differentiated into two main facies groups: a limestone facies and a graywacke facies. The limestone facies is outstanding in terms of area, as it extends over much of Papua including the central foothills and the Fly-Digoel shelf regions. Thick accumulations of graywackes are situated to the north and east of the limestone regions. These two main facies apparently grade laterally into one another and the transition zones are marked by the occurrence of marls, mudstone and siltstone. In addition local variations in lithology have been described (e.g., a conglomeratic phase of the graywacke facies) which are very significant from the tectonic point of view.

Limestone facies.-- Middle Miocene limestones have a widespread development throughout the central foothills and the Fly-Digoel shelf regions of western Papua (Fig.6). As was the case for the Upper Miocene, these limestones

MIDDLE MIOCENE ISOPACHS AND LITHOFACIES

Figure 6



also can be subdivided on the basis of their dominant lithologic aspect into two limestone subfacies. On one hand there are fragmental, reef-shoal-type limestones and on the other there are fine-grained, argillitic limestones.

The fragmental reef-shoal limestones play a subordinate role in the Middle Miocene limestone development. Subsurface information indicates that these limestones occur in a band which parallels the coast of Papua from Komewu to the Morehead bore on the Oriomo Plateau. However, these limestones may cover a larger area of the Fly-Digoel shelf than is shown by this limited information. In the Morehead bore the undifferentiated Middle to Upper Miocene section has been described to consist of clean, white, shoal-type detrital limestone. Again at Komewu No.2 the bore passed through an undifferentiated Upper to Middle Miocene sequence composed predominantly of algal, detrital limestones.

The argillaceous limestone and marl facies is much more widely distributed throughout Papua in surface exposures. It occurs as a thin (100 to 250 meters) blanket throughout most of the central foothills. Similar chalky limestone with detrital limestone and silty marls also occurs at Aramia on the Fly-Digoel shelf and appears to be the forerunner of the identical lithologic association that developed there in the Upper Miocene. Throughout the whole area shown on Figure 6 the argillaceous limestone facies includes only minor intercalations of marly silts, marls and mudstones. Some of the limestones, such as were taken from the Omati bore, are mainly of the pelagic variety.

To the east the argillaceous limestones grade laterally into marls. At Kuru marl forms the upper 30 meters of a sequence 250 meters in thickness composed of argillaceous limestone. Farther east the Middle Miocene is entirely represented by marl as in the Bwata, Puri and Wana bores. In these latter localities an abundant Orbulina fossil fauna is found in the marls.

Mudstone-siltstone facies.-- The northern margin of the argillaceous limestone terrain west of Mendi is fringed by a belt of mudstones ranging in thickness from 250 to 900 meters. In the Ok Tedi area this facies is represented by a predominance of mudstones and siltstones with intercalations of argillaceous limestones, detrital limestones, and some sandstone. To the east in the Strickland Gorge, and near Mendi, the Middle Miocene is still represented by mudstones associated with marls and siltstones. These rocks are apparently a transitional facies between the argillaceous limestones to the south and a graywacke belt which, as we shall see, is present to the north.

Sandstone-siltstone facies.-- In the Iwoer-Denom area of West Irian the Middle Miocene is represented by the development of approximately 1500 meters of micaceous sandstones and associated siltstones. These rocks (upper Iwoer Formation) have been placed in the Upper Miocene by Bär et al. (1961) but are also correlated with part of the "f₂₋₃" Stage on the basis of larger foraminifera (Bär et al., Fig.10). Throughout Papua, petroleum geologists have used the "f₃" Stage as being equivalent to the Middle Miocene. In order to be consistent with the bulk of the Middle Miocene information, I am tentatively placing the so-called upper Iwoer Formation into the Middle Miocene.

The Middle Miocene (?) micaceous sandstones of the Star Mountains region are associated with siltstones, shales, marls and intercalations of calcareous subgraywacke-type sandstones. The sandstones are poorly sorted, thick-bedded and very often cross-laminated. Some of the lower sandstone units are locally conglomeratic. Slate fragments are common throughout the sandstones. Marly limestones, lignitic streaks and occasional coal layers occur in the upper 60 meters of the unit.

Graywacke-mudstone-conglomerate facies.-- A Middle Miocene graywacke-mudstone-conglomerate facies is developed along the northeastern edge of the central foothills in the area drained principally by the Pio, Tsoma and the Aure Rivers. Perhaps the most complete section of these rocks is exposed along Mare Creek, a tributary of the Pio River. There Kent and Rickwood (LW, 1956) reported 1900 meters of graywacke, siltstone and mudstone including a subordinate conglomerate unit 15 meters in thickness. This conglomerate was composed of pebbles of quartz, quartzite, limestone, slate, basalt, andesite, diorite and granodiorite, all in a mudstone matrix.

Conglomerate beds are more numerous in Middle Miocene sedimentary sequences exposed in other localities throughout the Pio-Purari region. For instance Kent and Rickwood reported a partial section (190+ meters) of mudstone exposed in the Pio River near Hui Creek which was intercalated with conglomerate beds spaced at intervals of about 15 meters. The clasts of the conglomerates (Pio conglomerates) were dominantly limestone in contrast to the solitary conglomerate unit

found in Mare Creek. Furthermore, many of the pebbles contain derived Lower Miocene, Eocene and Cretaceous fauna materials. In another locality in the Pio region rounded limestone boulders of up to 1.5 meters in diameter have been found in the conglomerate units. Most of these mudstone-conglomerate sequences also display a great deal of slumping.

Farther to the northeast in the upper Tsoma region over 2000 meters of Middle Miocene mudstone, graywacke and conglomerate have been reported. In the most northeastern part of the Pio-Purari region investigated by Kent and Rickwood, the graywackes appear to be at least partially replaced by beds of marine siltstones and mudstones intercalated with coal seams.

In the central cordillera region Rickwood (1955) assigned 1150 meters of fossiliferous graywackes, conglomerate, impure limestone and shale to the Middle Miocene. A thin conglomerate bed near the base of this unit contains pebbles of limestone and metamorphic rock. The strongly tuffaceous upper graywacke units contain fragments of basic volcanic material.

1.4.2 Middle Miocene Diastrophic Framework

The distribution, lithology and thickness of Middle Miocene rocks developed in Papua are suggestive of two main tectonic environments of sedimentation (Fig.7). First, there was a platform environment characterized by stable to mildly unstable conditions of sedimentation. This platform environment corresponds to the areas of limestone deposition as described in the preceding pages, i.e. the Fly-Digoel shelf and the central foothills area. Secondly, the thick graywacke sequences in the Pio-Purari

area are typical of true geosynclinal conditions of deposition and it is thought that a rapidly subsiding geosynclinal zone bordered the northern margin of the platform during the Middle Miocene. There is also evidence to suggest that parts of the present highlands region were already actively rising in the Middle Miocene.

Erave-Wana swell.-- An important and perhaps the best defined Middle Miocene tectonic element in Papua is the Erave-Wana swell. Petroleum geologists working in Papua applied this term to a broad (75-200 kilometer) positive area lying between the stable platform of the Fly-Digoel shelf to the southwest and a geosynclinal zone to the north and northeast. The presence of this structure was inferred from the general thinning and sometimes complete absence of Middle Miocene rocks in the Erave-Wana area. On the basis of the isopach distribution it appears that the Erave-Wana swell extends from the headwaters region of the Strickland River southeastward for 100 to 200 kilometers. At about the site of Mount Bosavi the axial trace of the swell swings eastward. This change of trend is also accompanied by increasing definition along the northern margin of the swell. The locus of maximum Middle Miocene uplift may have been in this east-west sector as no Middle Miocene rocks are found in a 5000 square kilometer area lying between the Kikori and Erave Rivers. Between Mount Murray and the Delta embayment the swell broadens and swings southward, hence giving it a generally sigmoidal pattern.

As indicated in Figure 6 the structure was strongly asymmetrical to the north and northeast. This fact alone

MIDDLE MIOCENE DIASTROPHIC FRAMEWORK

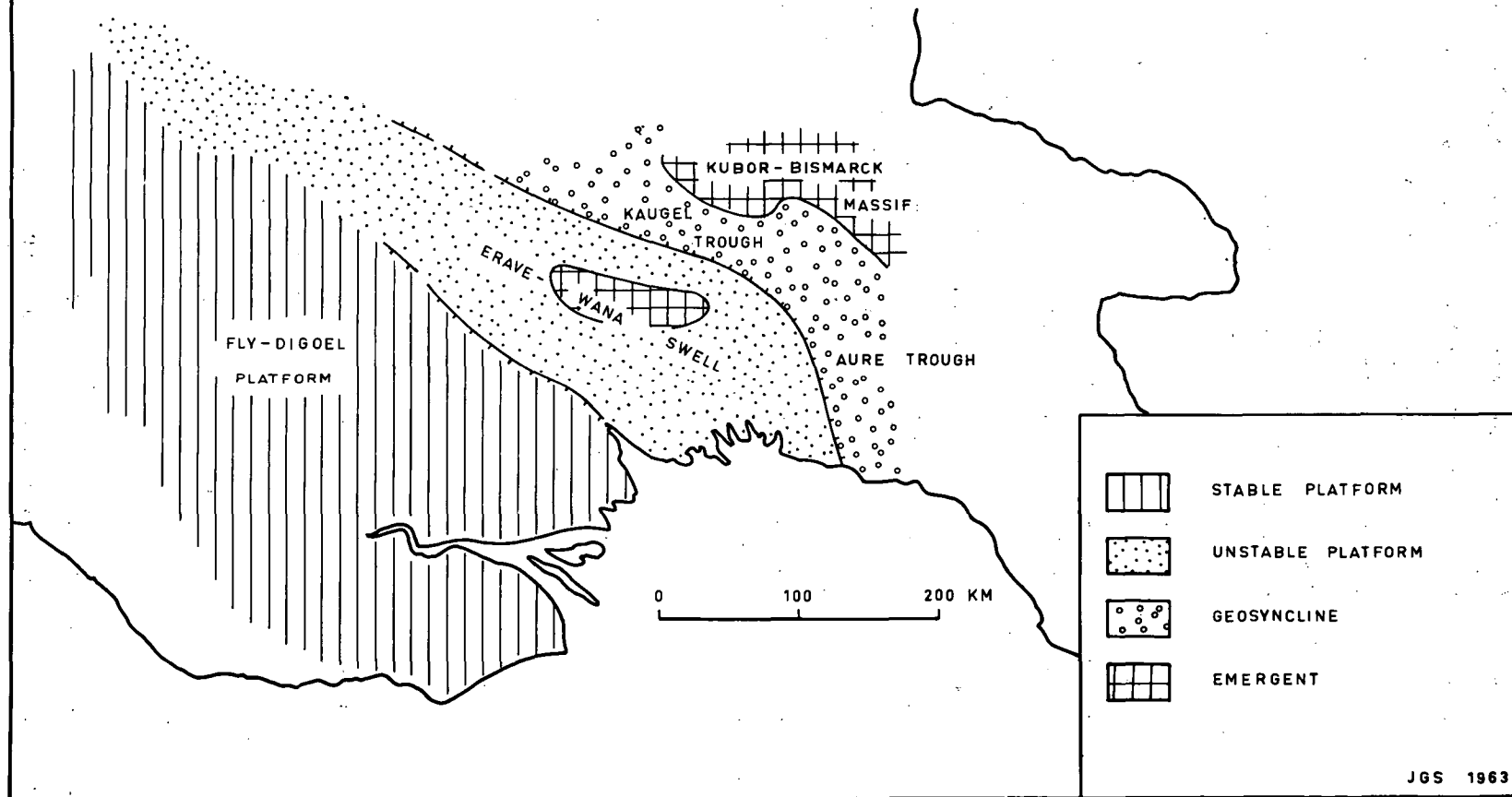


Figure 7

indicates the tectonically active nature of the northern border of the swell. In addition to this morphologic evidence, the nature of the sediments developed adjacent to this margin; i.e., the Pio conglomerates, attest to intense tectonic instability which enhanced the processes of erosion and denudation on the swell. The extremely coarse nature and profusion of the Pio conglomerates led Kent and Rickwood to the conclusion that they were derived from fault scarps forming on the northeast margin of the Erave-Wana swell which was emergent during much of the Middle Miocene. This emergence is indicated by the absence of Middle Miocene rocks in some areas (Fig.6) and by the presence of considerable quantities of derived Lower Miocene, Eocene, Cretaceous material in the Pio conglomerates. However, the peculiar conglomerate unit exposed in Mare Creek, containing plutonic, metamorphic, and volcanic rock fragments, indicates that coarse detritus was being derived from the north, probably from the vicinity of the present Kubor or Bismarck Ranges, and was finding its way into the geosynclinal trough. It seems quite unlikely that these materials were derived from the Erave-Wana swell, although such a possibility can not be denied.

The rocks which developed on the swell itself; i.e., argillaceous limestones and marls, are such that would be expected to develop in an epineritic environment on an unstable shelf. I interpret the Erave-Wana swell as a hinge zone which was foundering between the more stable condition existing on the platform to the southwest and the extremely active geosynclinal belt to the north and east.

Geosynclinal belt.-- The nature and thickness of the sediments developed in the Pio-Purari region northeast of the Erave-Wana swell indicate that during the Middle Miocene an active phase of geosyncline development was in progress. However, the restricted outcrop of these rocks make it difficult to analyze the original extent of the geosynclinal belt. In the Pio-Purari region the work of Kent and Rickwood (LW, 1956) has established the geosynclinal limits shown on Figure 7 and described above. Eastward beyond the Pio-Purari region the geosynclinal graywacke belt swings southward through the Kukukuku lobe and includes the so-called Aure trough which was developing in that region during the Middle Miocene. I have called the westerly-trending segment of the geosynclinal belt the Kaugel trough.

The main problem of interest in this discussion is the western and northern extensions of the Kaugel trough. It is probable that the northern margin of the Middle Miocene geosynclinal trough was formed by an emergent landmass, at least in the zone to the northeast of the Pio-Purari region. The presence of this emergent zone is suggested by the occurrences of siltstones, mudstones and coal in the upper Tsoma River area which in turn are indicative of a marine to transitional environment of deposition. Furthermore, the crystalline components; e.g., basalt, diorite and granodiorite, of the conglomerate found at Mare Creek could have been derived only from a terrain such as now found in the Kubor and Bismarck Ranges of the central cordilleran region. There is, however, little information to indicate the regional extent and trend of this crystalline massif, the Kubor-Bismarck massif.

There is also very little information concerning the westward extent of the Middle Miocene geosynclinal trough beyond the Pio-Purari area. The graywackes that Rickwood reported in the central cordilleran region indicate that the geosyncline may have trended west-northwestward paralleling the northern margin of the Erave-Wana swell. This is also suggested by the general northerly thickening of the mudstone and siltstone sequences in the Strickland Gorge-Mendi region. These rocks probably represent a transitional facies from the argillaceous limestones developed on the Erave-Wana swell and a geosynclinal trough which existed to the north.

The sandstone facies developed in the Star Mountains may have developed in an isolated sedimentary basin. The coarse nature of the sands together with the presence of slate fragments and coal seams indicate that these rocks were deposited in a shallow, slowly subsiding basin bordered by a rising zone to the north. One can only suggest that this basin developed in a more or less unstable platform environment. It is not considered to be the western extension of the Kaugel trough.

Fly-Digoel platform.-- As in the Upper Miocene the lithologic associations and the thickness of the rocks developed in the Fly-Digoel shelf indicate that the area behaved more or less as a stable platform. However, the increase in thickness and the greater argillitic content of the limestones at Aramia suggest that mildly unstable conditions may have existed locally in parts of the region. The isopach distribution suggests that the Fly-Digoel platform had the configuration of a broad, shallow basin.

1.5 LOWER MIOCENE DIASTROPHISM

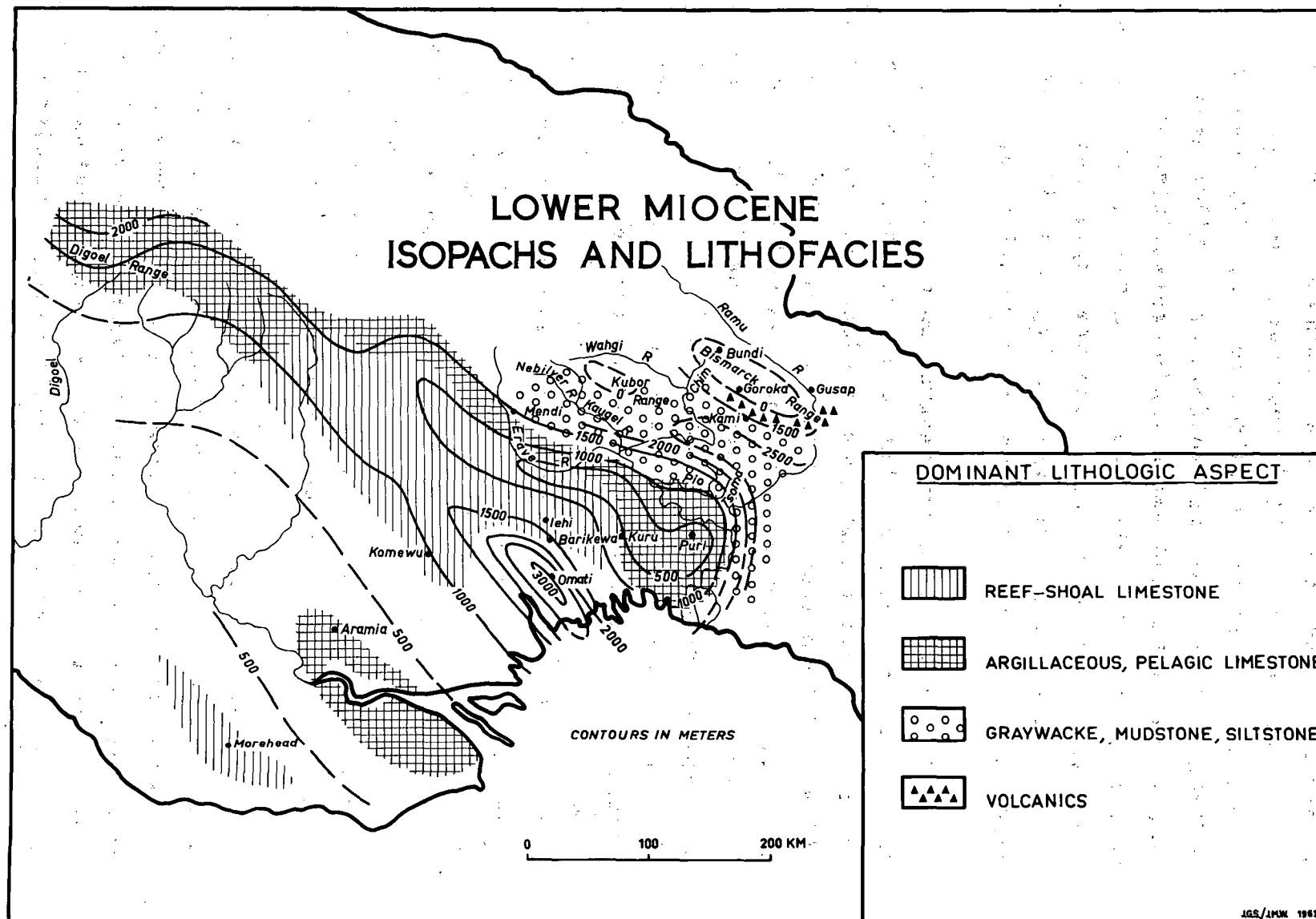
1.5.1 Lower Miocene Rocks

The following discussion is primarily a description of the lithologic character and distribution of rocks occurring in western Papua which correspond to the "e" and "f₁₋₂" Stages in the East Indian nomenclature of van der Vlerk and to the Kereruan ("e") and Taurian ("f₁₋₂") Stages of the local Papuan terminology. Eames et al. (1961) have shown that these stages are equivalent to the Aquitainian and Burdigalian Stages, respectively, of the European Lower Miocene.

Limestone facies.-- The Lower Miocene was a period of important limestone development in Papua. As can be seen on Figure 8 limestones have a very widespread distribution extending throughout the central foothills and the Fly-Digoel shelf regions and in some localities the limestones attain outstanding thickness. In general one can recognize two limestone subfacies; viz., argillaceous limestones and reef-shoal limestones. During the Lower Miocene periods of limestone deposition the tectono-environmental conditions of deposition in these regions apparently fluctuated somewhat and in any one locality the section may comprise a complex mixture of these lithologies.

The outstanding feature of the Papuan Lower Miocene limestone realm is the very thick section which was discovered in the Omati No.1 bore. This bore penetrated

Figure 8



nearly 3100 meters of Lower Miocene limestone. The upper 1000 meters consist predominantly of algal and coralline, detrital, shoal limestones. The remainder of the section is comprised of dense argillaceous limestones with about 200 meters of detrital limestone occurring near the bottom of the sequence. An additional 450 meters of Lower Miocene rock are exposed at the surface around the Omati well making a total of about 3500 meters of Lower Miocene in the Omati area.

This thick occurrence gave geologists working in Papua cause to propose that a deep trough, which they called the Omati trough, was developed in Lower Miocene times in the southern part of the central foothills region. This trough is further defined by the reef-shoal-type limestone occurrences in the Komewu, Barikewa and Iehi bores and in the Kanau anticline which suggest that the trough trended northwestward from the Omati area. The thickness of limestone at these localities ranges between 1000 and 1500 meters and is considerably greater than in the surrounding area of the central foothills and the Fly-Digoel shelf. However, it is also quite a bit less than the extraordinary thickness encountered in the Omati bore, which is quite a thickness of limestone to have accumulated in the relatively short span of the Lower Miocene. There is no evidence that these rocks have been thickened tectonically.

To the south of the Omati trough on the Fly-Digoel shelf, and on the Oriomo Plateau, the Lower Miocene rocks are considerably thinner (200 to 700 meters) and consist, as at Morehead for instance, of detrital limestones, sandy limestones and some fine sandstone with siltstone and mudstone intercalations. A series of

argillaceous limestones and marls 440 meters thick comprises the Lower Miocene at Aramia.

To the north of the Omati trough the isopachs indicate a thinning and in general define a northwest to southeast-trending structure which represents the Lower Miocene development of the Erave-Wana swell. The limestones, that developed on the swell, are for the most part fine-grained, argillaceous, pelagic limestones. In the Puri area the Lower Miocene is represented by 440 meters of argillaceous, pelagic limestones (Puri Limestone) with minor occurrences of shoal limestone at the base. These limestones produced a limited amount of oil and gas shortly after drilling of the Puri No. 1 well (Commonwealth of Australia, 1961a). Similar limestones are developed over a wide area of the eastern end of the Erave-Wana swell in the Puri-Kuru-Wana region. Westward they appear to represent a transitional facies between the detrital limestones, which developed on the crest of the swell, and the graywackes to the north. In the Erave area near Mendi Rickwood (KR,n.d.) found the lateral variation in facies to be especially well developed. There the pelagic or so-called basinal limestone facies belt was about 10 to 15 kilometers wide.

Still farther west in the Strickland and Fly headwaters region Lower Miocene rocks are represented by an alternating sequence of argillaceous and detrital limestones with some interbeds of siltstone and mudstone. The gross pattern of distribution is like that occurring to the east; i.e., detrital reef-shoal limestones grading northward into dense, argillitic pelagic limestones.

A similar suite of limestones has been described by Bär et al. (1961) in the Star Mountains. These rocks, which are exposed in the highest parts of the Digoel and Juliana Ranges (elevation 2540-4800 meters), include thin-bedded marly and argillitic limestones associated with reef-type calcarenites and some dolomitic limestones. These sequences (New Guinea Limestone group) range in thickness from 2600 to 3600 meters.

Graywacke facies.-- The most important phase of graywacke deposition in the western Papuan geosynclinal system occurred during the Lower Miocene. This fact is witnessed by the widespread and thick occurrences of graywackes in the northern part of the central foothills region. In the area north of the Erave-Wana swell the graywackes are associated with abundant mudstones and minor conglomerates and limestones. These rocks are generally considered to be late Lower Miocene (Taurian).

Detailed information concerning the graywackes is scarce and permits only a rough approximation of the distribution and lithologic character of these accumulations. Rickwood (KR,n.d.) assigned about 1500 meters of graywacke exposed in the Iaro syncline near Mendi to the Lower Miocene. It is likely that a continuous belt of graywacke deposition extended eastward from the Mendi area to at least the Pio-Purari region. In the latter area, Kent and Rickwood (LW,1956) reported at least 2700 meters of sediments including graywackes, siltstones and mudstones. They described the graywackes as being medium-grained, rich in ferromagnesian minerals, subangular quartz and calcite.

Immediately east of the Pio-Purari region the trend of the graywacke belt swings sharply southward and extends into the Kukukuku lobe (Fig.8). This meridional extension of the graywacke belt is referred to as the Aure trough. During both the Lower and Middle Miocene a very thick (3000 to 6000 meters) sequence of alternating graywacke and mudstone accumulated in the Aure trough, the so-called Aure facies. A detailed consideration of the lithologic characteristics of the Aure facies is beyond the realm of this dissertation. However, because there is very little information concerning the equivalent graywackes of western Papua, it seems appropriate to briefly review the main petrologic characteristics of the Aure facies as revealed by the studies of A.B. Edwards (1950b). Although recent paleontologic work has demonstrated that Edwards' particular samples are Middle Miocene, his descriptions are in general typical of the entire Aure facies including the Lower Miocene.

Edwards describes the graywackes of the Aure trough as:

... containing abundant marine micro-fossils and plant fragments. The graywackes are illsorted rocks but show prominent graded bedding and occasional slump structures. They consist essentially of angular grains of basic plagioclase, hornblende and pyroxene, with a minor amount of other minerals, together with numerous rounded rock fragments in a prominent clay matrix. The rock fragments consist largely of a variety of andesites, together with fragments of schist, mudstone, reef quartz and other rock types. Both graywackes and mudstones closely approximate the average andesite in chemical composition.

By calling these rocks graywackes, Edwards has placed the emphasis on the processes of sedimentation rather than on the composition. Hence, he concludes that:

... the conditions attending deposition, the abundance of fresh angular fragments of chemically unstable minerals and extremely illsorted character of the sediment establish that the Aure sediments belong to the class of sediments that has been described by Fischer (1933) as 'poured-in' sediments. The characteristic rock of this group of sediments with a grainsize comparable to that of the Aure sediments is the graywacke.

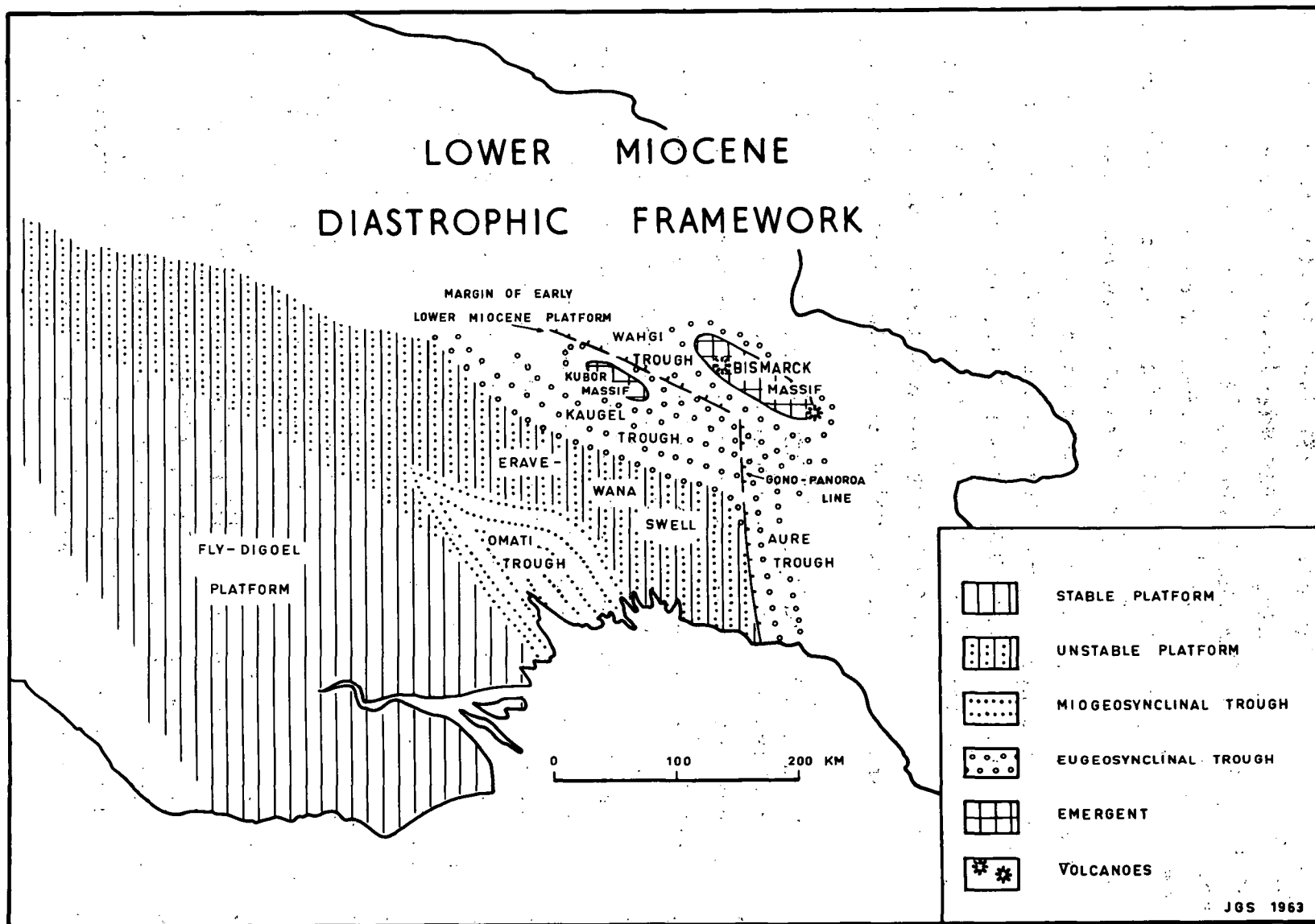
I would prefer to call the Aure sediments epiclastic volcanic rocks in the sense of R.V. Fisher (1961) emphasizing the important and rather unique volcanic content of these accumulations. However, arguments concerning petrographic nomenclature are beyond the scope of this report and to avoid unnecessary confusion the Aure-type sediments will be referred to as graywackes; a term which is firmly entrenched in the geologic literature of Papua.

Other rocks.-- I have described the limestone and graywacke facies which apparently had the most widespread and thickest development during the Lower Miocene phases of geosyncline formation in western Papua. But there are several other suites of rocks that played a more limited but nevertheless important role in the framework of the Lower Miocene sedimentation. These include the volcanics, black shales and graywackes which are developed in the central ranges of New Guinea and formed part of the northern margin of the Papuan geosyncline during the Lower Miocene. The description of these rocks will be included in the discussion of the diastrophic framework of the hinterland zone.

1.5.2 Lower Miocene Diastrophic Framework

The Lower Miocene was a critical phase in the diastrophic development of the Papuan geosynclinal system. Several very important alterations in the tectonic

Figure 9



framework of sedimentation were made during this period. The most outstanding of these developments was the fragmentation and subsidence of large crustal blocks that were originally part of a platform which during the early Lower Miocene extended well into the heart of the present New Guinea orogen (Fig.9). Also of fundamental importance was the appearance of an embryonic geanticlinal system destined to grow into the main New Guinea orogenic belt. Both these processes; namely, the fragmentation of the platform and the rise of the geanticlinal ridge, produced a complex of intra-geosynclinal troughs which were constituent elements of the main Papuan geosyncline.

Extent and development of the platform.-- The lithologic character of Lower Miocene rocks, especially the Kereruan (early Lower Miocene or "e" Stage) rocks, indicates that platform conditions of deposition were far more extensive than in the later Tertiary. It appears that in the late Lower Miocene or Taurian this platform was split into a series of troughs which became the site of geosynclinal sedimentation. However, this latter point is reserved for subsequent consideration and the next few pages will be concerned with the evidence suggesting the limits of the early Lower Miocene platform. On the basis of Figure 8, which illustrates the lithofacies distribution for the entire Lower Miocene, it is reasonable to suppose that the eastern edge of the platform is represented by the transition from the argillaceous limestone of the Wana-Puri region to the graywacke of the Kukukuku lobe. Hence, the eastern edge of the platform for the Lower Miocene may be defined as a northward-trending zone roughly paralleling the lower Purari River and extending northward to the Pio River.

During the Kereruan the eastern margin of the shelf was apparently unchanged, but the northern margin was situated farther north. In the course of the Pio-Purari survey Kent and Rickwood (LW, 1956) discovered that during the Kereruan the discontinuous reef-shoal limestones forming in the Pio-Purari area and to the north were abruptly separated from geosynclinal rocks to the east along a north-south trending line roughly following the present Tsoma River. They called this transition zone the Gono-Panoroa line. From the relationships observed in the field they inferred that the attenuated Kereruan development to the west of the Gono-Panoroa line indicated emergent to shallow platform conditions. The graywacke-type geosynclinal sedimentation was restricted to the regions east of the Gono-Panoroa line. It is apparent from these observations that the Gono-Panoroa line was an important feature in the diastrophic framework of the Kereruan and is probably best interpreted as the edge of the tectonic platform.

In the Lower Wahgi River region Rickwood (1955) has described early Lower Miocene (Kereruan) fragmental limestones containing Miogypsina and has suggested a shallow water origin for these sediments. These rocks are quite similar to the Kereruan rocks in the Pio-Purari and may also represent a stable or mildly unstable platform environment indicating that geosynclinal subsidence had not yet begun in the central cordillera. Similar reef-shoal limestones are developed in the lower part of the Lower Miocene sequence in western-most Papua as in the Lavani Valley and in the Fly-Strickland headwaters region.

Hence, the early Lower Miocene platform appears to

have had a general rectangular outline and extended well into the heart of the present New Guinea orogen. In Taurian times (late Lower Miocene) the outline of the northern margin of the platform was altered considerably by fragmentation of this platform producing geosynclinal subsidence and deposition.

It may be well to note that in the Eastern Highlands District, east of the Gono-Panoroa line, McMillan and Malone (1960) have reported a very thick (1000 - 3000m.) sequence of early Lower Miocene graywackes, mudstones, conglomerate, tuffs, agglomerates and andesite flows. However, these occurrences bordered the northern margin of the Kereruan Aure trough.

Erave-Wana swell.-- In the preceding pages I have defined the limits of the stable platform as it existed during the Kereruan. However, the general platform tectonic regime can be divided into three main tectonic subunits which were in existence during the entire Lower Miocene; viz., the Erave-Wana swell, the Omati trough and the Fly-Digoel platform. The most northern of these is the Erave-Wana swell. I have already described the Middle Miocene development of the swell which had a similar morphology but was developed on a larger scale. The swell forms the northern margin of the late Lower Miocene shelf. The swell was 60-100 kilometers broad and was bordered on the southwest by the Omati trough, the site of the thick Lower Miocene limestone deposition.

The swell developed important definition in the Lake Kutubu area and trended east-southeastward to the upper Purari River region where it broadened considerably

and the main axis trended in a more southerly direction. As I have mentioned in the description of the lithology, the Erave-Wana swell was the site of considerable limestone deposition with reef-shoal limestones forming on the crest of the swell and grading north and eastward into argillaceous "basinal" limestones and finally into graywackes.

An important characteristic of these argillaceous limestones and associated calcareous mudstones, situated in the transition zone on the northern margin of the Erave-Wana swell, is the development of strong slump folding. Kent and Rickwood state that some of the U-folds, which are lying flat, consist of about 1.5 meters of overturned sediment with a fold amplitude 12 meters. The graywackes associated with these sediments are less strongly slumped. This slumping may have resulted, as Kent and Rickwood suggest, by penecontemporaneous slumping on a pre-existing slope or by a process of intermittent tilting and faulting.

Another important morphological characteristic of the Erave-Wana swell is the fact that to the west it merges with the Fly-Digoel platform, and, as was the case in the Middle Miocene, it can be thought of as an unstable edge of the platform or hinge zone separating the more stable parts of the platform from the mobile geosynclinal terrain to the north.

Omati trough.-- The Omati trough is the term applied to a northwest-trending basin which was situated within the platform regime during the Lower Miocene. The presence of this basinal trough has been inferred by geologists because of the very thick accumulations of limestone

penetrated in the Omati bore. The trough trends northwestward from the Omati area and becomes shallower as witnessed by limestone thicknesses. On the isopach map (Fig.8) I have ended the trough in the vicinity of Mount Bosavi. However, there is a possibility that this trend continued still farther as a shallow furrow into the upper Strickland area.

The 3000-3600 meters of argillitic limestone and reef-shoal limestone at Omati represent an almost incredible amount of sediment to have been deposited within the relatively short period of the Lower Miocene. However, there is no evidence of tectonic thickening in the Omati bore where the rocks are nearly horizontal. As I have previously described, the lower 1100 meters of the Omati section is comprised almost entirely of fine-grained, argillitic, dense limestones. It is likely that during the accumulation of these rocks the Omati trough was rapidly subsiding but limestone deposition was keeping pace. The lithology seems to indicate conditions of deposition similar to those which would be expected on an unstable shelf possibly in an epineritic environment. Reef-shoal limestones are predominant in the upper part of the Omati sequence and suggest that the rate of subsidence, although still rapid, was overtaken by deposition and the locus of deposition was suitable for reef development as well as subject to more agitation by wave and current action. It is also evident that throughout the development of the trough, especially during the Taurian, the Erave-Wana swell was well defined and acted as an effective barrier to prevent the influx of terrigenous material from the north into the Omati trough.

The development of these thick limestone sequences

indicates that the Omati trough represented a miogeosynclinal element in the otherwise dominantly eugeosynclinal Lower Miocene Papuan orthogeosyncline. The limestones occurring in the western cordilleran region are also typical of a miogeosynclinal succession. This latter region appears to have been a mobile extension of the Fly-Digoel platform or hinge zone rather than a well-defined trough such as developed in the Omati region.

Fly-Digoel platform.-- South of the Omati trough the Lower Miocene rocks appear to be spread in a relatively even blanket ranging in thickness between 190 and 780 meters. The paucity of information makes it possible to define only the broadest structure, and it appears that the tectonic environment in these areas was that of a slowly sinking, mildly unstable shelf.

Geosynclinal belt.-- In the previous pages, I have made some reference to the development and distribution of the Lower Miocene geosynclinal troughs. However, there are several points which need to be clarified and summarized.

In the early Lower Miocene geosynclinal deposition was confined to the Aure trough which was situated to the east of the Erave-Wana swell; i.e., east of the Gono-Panoroa line. Edwards' study (1950b) of the Aure graywackes has provided some insight into the probable tectonic environment of Lower Miocene, graywacke sedimentation in that region. Edwards concluded that the bulk of the graywacke of the Aure trough

. . . appears to be derived from a mountainous terrain, by the erosion of widespread andesitic tuffs, under

climatic conditions similar to those now prevailing in the area; and they were deposited in still, moderately deep water, free from all but weak current action, and close to a shore line. Deposition was probably accompanied by subsidence of the floor of the receiving area.

Previous workers in Papua have suggested the presence of a volcanic belt lying to the east of the Aure trough in the vicinity of the Tauri River as a source of these graywackes. Presently, I will discuss a geanticlinal island system which formed at least part of the northern border of the Aure trough and may also have been a source of much of the volcanogenic sediment.

During the upper part of the Lower Miocene (Taurian) the northern margin of the shelf began to subside and eugeosynclinal conditions, including the deposition of graywackes, began to encroach upon the shelf from the north. In essence this new region of subsidence was a west-northwesterly prong of the pre-existing Aure trough. The regional extent of this trough is roughly defined by occurrences of graywacke sequences in the Mendi area, the Nebilyer Valley, a tributary of the Kaugel River, and in the Pio-Purari River area. There is no information to indicate how far this geosynclinal trough (Kaugel trough) extended westward beyond the Mendi region. Figure 9 illustrates the development of the Kaugel trough at the expense of the pre-existing shelf.

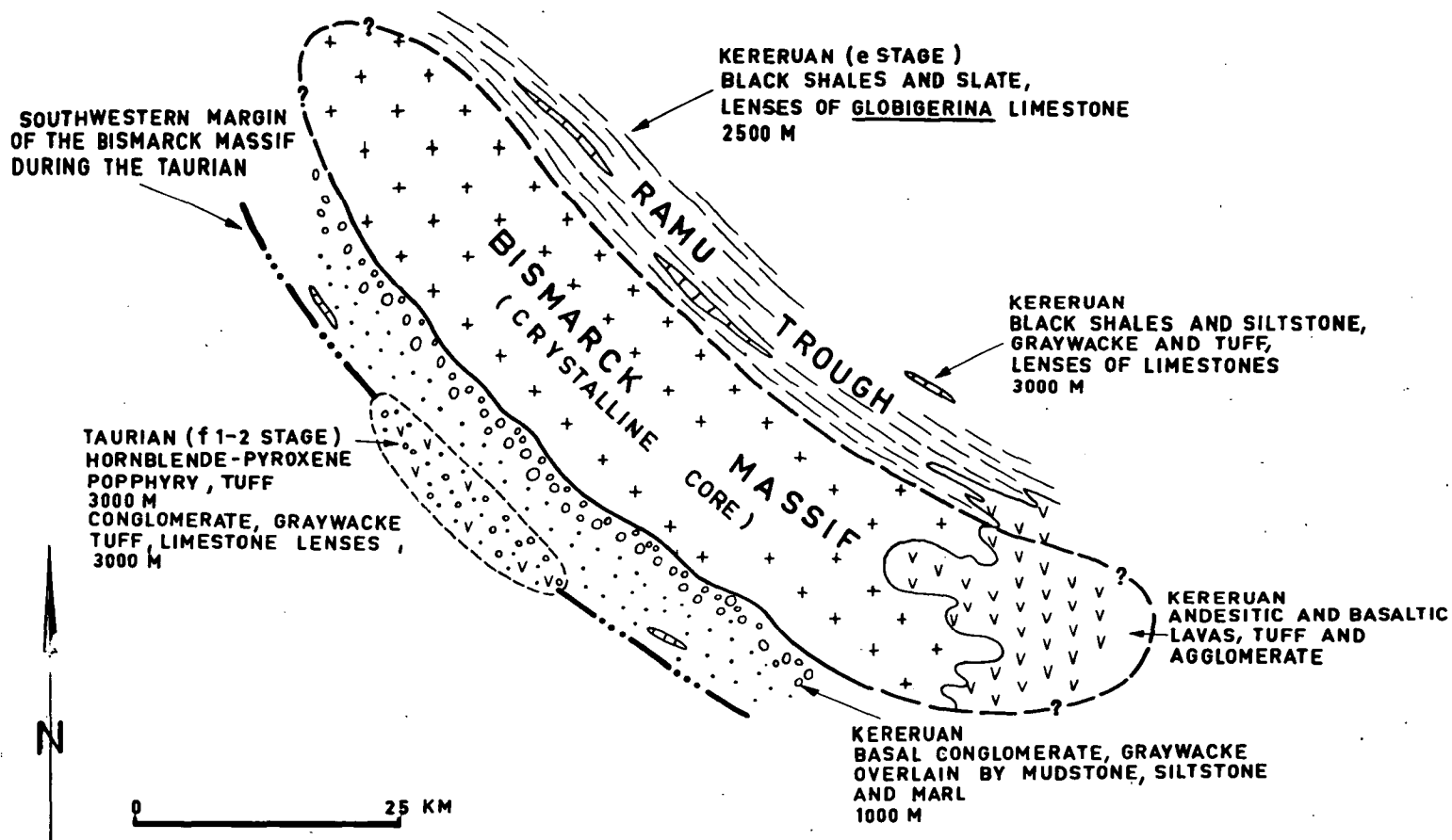
Bismarck and Kubor massifs.-- In the previous chapters concerning the Pliocene, Upper and Middle Miocene diastrophic framework, I have made constant mention to the existence of a positive region situated in the hinterland zone beyond the northern border of the main Tertiary geosynclinal troughs. Although the geologic information

and the overall regional relationships did in fact suggest the presence of this geanticlinal system, the specific information was too scattered and it was impossible to give a concise picture of the nature of this positive mass. However, the information is present in sufficient quantity and detail to outline the Lower Miocene development of the hinterland zone.

The following interpretation is based primarily on the findings of McMillan and Malone (1960) in the Eastern Highlands District of New Guinea, especially the region surrounding the eastern end of the present Bismarck Range. The observations made by McMillan and Malone suggested to them that at least part of the Bismarck Range was emergent during the Lower Miocene. I am in agreement with their conclusion and wish to develop the thesis that this emergent zone, which I will call the Bismarck massif, represented an embryonic phase in the development of the geanticlinal system which formed within the heart of the Papuan geosyncline during the Tertiary.

Throughout much of the region mapped by McMillan and Malone the early Lower Miocene (Kereruan) sediments rest directly on, and encircle, the old metamorphic-plutonic complex of the Bismarck massif (Fig.10). Along the Ramu River, which forms the northeast boundary of the massif, there are important occurrences of early Lower Miocene rocks. This latter early Lower Miocene sequence consists predominantly of dark shale, slate and siltstone, all with lenses of Globigerina limestone. Graywackes and tuffs are of minor importance but become more common toward the southeastern end of the massif near Gusap on the Ramu River (Fig.8). In the Ramu River valley the

Figure 10



LOWER MIOCENE DEVELOPMENT OF THE BISMARCK MASSIF

JGS 1963

Kereruan rocks are probably 2500-3000 meters thick.

The so-called Asai beds which Dow and Dekker (1963) have observed in the western Bismarck Range include shale, siltstone and phyllite, and are probably part of this same facies belt.

The thickness and lithologic character of the sediments in this zone, which I have called the Ramu trough, suggests that they were deposited in a rapidly subsiding geosyncline and probably in a bathyal environment. There is not enough known about the petrology of these sediments to suggest a source, but I have the impression that very little of the sediment came from the emergent Bismarck massif to the south. It is more likely that the sediment was derived from a source located to the north of the Bismarck massif. This northern region was presumably also the source of the thick graywacke, argillite, conglomerate and agglomerate sequence which accumulated in the Finisterre Range during the early Lower Miocene (Ongley, GN, 1939). Hence, the northern margin of the Bismarck massif is thought to have played a very passive role as far as providing a source of sediment for the Ramu trough.

In contrast the southern margin of the Bismarck massif was the site of active tectonism during the deposition of the early Lower Miocene. The basal conglomerate units of the Kereruan rest directly on the crystalline Bismarck massif. This conglomerate, which is 160-330 meters thick, consists of subangular pebbles, cobbles and boulders of igneous rocks, slate, schist and other metamorphic rocks in a graywacke matrix. These coarse clastic materials were undoubtedly derived from a

tectonically active metamorphic-plutonic terrain to the north. Figure 10 shows the distribution of these conglomerates and the outlines of the hypothetical source area, the Bismarck massif. The remainder of the Kereruan rocks that developed on the southern side of the massif consist of micaceous graywacke and grit, calcareous graywacke siltstone and shale. Overlying these basal units are siltstones, sandy siltstones, calcareous marls, limestone and graywacke. This makes a total of about 1200 meters. Hence, it can be seen that there is quite a contrast between the dominantly clastic, relatively thin (1200 meters) early Lower Miocene sequence on the south side, and the thick, fine-grained sediments developed on the north side of the Bismarck massif in the so-called Ramu trough.

Volcanic rocks were accumulating near the eastern end of the Bismarck massif during the early Lower Miocene. These accumulations include flows of both andesitic and basaltic lavas with associated tuffs and agglomerates. During the Taurian or late Lower Miocene the volcanism associated with the Bismarck massif was far more extensive. McMillan and Malone have described a thick (3000 meters) accumulation of continental volcanics which consists of hornblende-pyroxene porphyry and tuff. These rocks, which they call the Daulo Volcanics, are exposed south of Goroka in a northwest-trending belt that probably approximates the margin of the Taurian Bismarck massif (Fig. 10).

An equally thick (3000 meters) accumulation of conglomerates, graywackes and tuff with minor limestone lenses are associated with and grade laterally into the Daulo Volcanics. These rocks (Asaro Conglomerates) are the products of rapid erosion and denudation of the Daulo

Volcanics and were deposited in the trough bordering the southern margin of the Bismarck massif.

Additional calcareous, late Lower Miocene units occur south of the volcanics and conglomerates. These include fossiliferous gray shale and mudstone with lenses of limestone and bedded graywacke in the upper parts of the sequence which contain abundant plant fragments and coal. Lenses of conglomerate are also frequent toward the top of the calcareous sequence and contain derived fossil material representing the Upper Cretaceous, Eocene and Oligocene indicating that all such rocks were exposed on the Bismarck massif during the Taurian. The Taurian limestones, which were possibly deposited as reef or shoal zones fringing the massif, contain abundant foraminifera.

Hence in summary it appears that during the Lower Miocene the Bismarck massif was one of a possible series of islands which bordered the northern margin of the Aure trough and its northwestern extension, the Kaugel trough. The island was probably at least 100 kilometers long and 15 to 30 kilometers in width. It was bordered on the north by a rapidly subsiding trench. The southern margin was the site of extensive erosion and denudation. The coarse clastic material derived from the crystalline core and later the volcanic mantle of the island were deposited along the southern side of the island.

It is quite likely that during the Taurian another massif similar to the Bismarck massif, and part of the same geanticlinal system, was developing in the area now occupied by the present Kubor Range. I have assumed

the presence of this massif on rather tenuous evidence. In the first place, the Taurian graywacke developed north of Mendi could not have been derived from the Erave-Wana swell to the south where limestones were deposited during the Taurian, thus the graywackes require a northerly source. In the second place the graywackes in the Nebilyer Valley contain occasional leaf fragments which might be interpreted as evidence that a land mass was rather close. Finally a more general line of evidence is the fact that the hypothetical Kubor massif has many of the tectonic characteristics of its neighbor the Bismarck massif; i.e., both these features have crystalline cores, during the Lower Miocene the Kubor massif, like the Bismarck massif, was bordered on the south by a graywacke belt and on the north by a zone of thick, dark shales such as have been described by Rickwood (1955) in the Gai Gorge northwest of the present Kubor Range. Hence, it appears as a distinct possibility that the hinterland zone north of the Lower Miocene geosynclinal troughs was likely to have been formed by a series of crystalline massifs of which the Kubor and Bismarck massifs were a part. The massifs represent an embryonic phase in the development of a geanticlinal system which grew and became consolidated during the Middle and Upper Miocene. Indeed, these small islands were the forerunners of the present orogen, the "backbone" of New Guinea.

1.6 PALEOGENE DIASTROPHISM

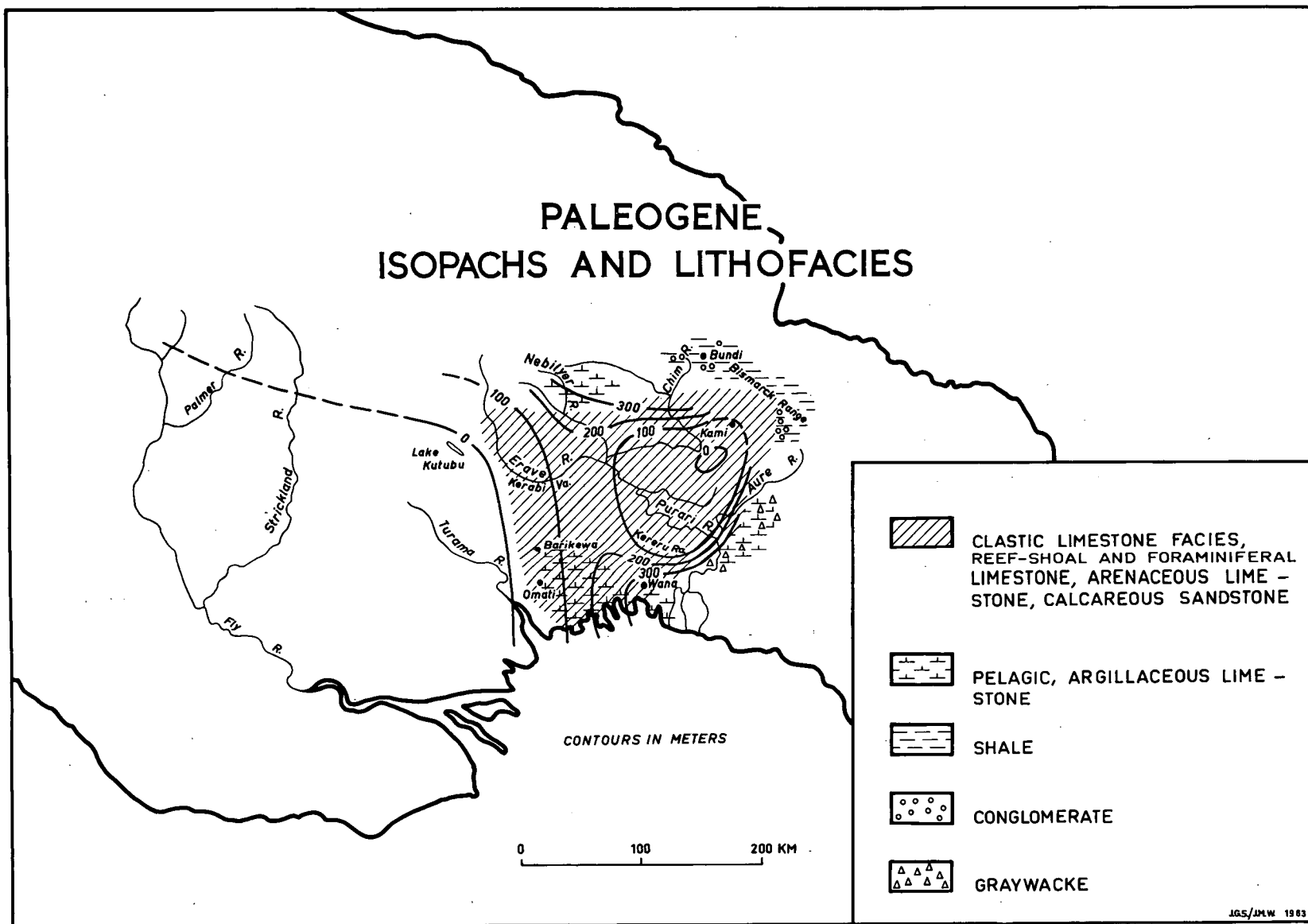
Pre-Miocene Tertiary rocks have a relatively restricted and patchy distribution in western Papua and the adjacent parts of New Guinea. In general the Upper Eocene rocks; i.e., "b₁-2" Stages of van der Vlerk, have the most widespread and continuous distribution. Middle Eocene and Lower and Middle Oligocene rocks occur only locally and there is some slight evidence to suggest that Paleocene rocks were deposited. Upper Oligocene rocks have never been reported in Papua.

For the purposes of this study all the Oligocene, Eocene and Paleocene (?) rocks occurring in Papua and the adjacent parts of New Guinea will be considered jointly as the Paleogene. The principal reason for doing this is that preliminary analysis of Eocene and Oligocene lithologic associations reveal very similar tectono-environmental conditions of deposition. In light of the irregular and incomplete distribution of these rocks individual consideration of each of these stages would be superfluous and tend to confuse the main problem; namely, the diastrophic framework of sedimentation.

1.6.1 Paleogene Rocks

Sequences of Paleogene rocks occurring throughout Papua (Fig.11) are usually quite thin with thicknesses generally ranging between 0 and 300 meters. They are

Figure 11



characterized by reef-shoal limestones or calcarenites, sandy limestones and calcareous sandstones, generally including abundant foraminifera such as Lacazina, Disocyclina, Nummulites and Operculina. There are several exceptions but for the most part this limestone facies is the dominant lithologic aspect of the Paleogene localities in western Papua. Therefore I will describe Paleogene occurrences from several areas which are typical of the main clastic limestone facies. In addition I will describe the variations from the normal lithologic association which are thought to be of particular environmental and tectonic significance.

Rocks found in the following localities in the central foothills region are typical of the Paleogene development throughout Papua. In the Kerabi Valley, for instance, the Paleogene consists of about 60 meters of fine-grained, well-bedded, reef and shoal limestones containing the foraminifera Lacazina sp. and Eorupertia sp.. In the Kereru Range the Paleogene is represented by at least 50 meters of calcarenite composed of echinoid plates and radioles. Other limestone units are composed almost entirely of the foraminifera Discocyclina and Lacazina. Siltstone pebbles, which are thought to be of Cretaceous origin, are found in the lower units of this sequence. Similar calcarenites occur in the Omati No.2 bore as part of a cyclical sequence of coarse calcarenite, fine calcarenite and "basinal" pelagic limestones. The distribution of this clastic limestone facies is clearly shown on Figure 11.

Rocks similar to the detrital limestone sequences developed in the central foothills are also found in the central cordilleran region of New Guinea. In the Eastern

Highlands District McMillan and Malone (1960) have reported several relatively thin, (less than 60 meters) sections of foraminiferal limestone and fossiliferous calcarenite containing Nummulites and Discocyclusina. Rickwood (1955) has reported a similar but thicker (530 meters) sequence of Paleogene rocks in the Chim Gorge. These consist of sandy limestone, calcareous sandstone and also foraminiferal limestone composed of Heterostegina sp. and Nummulites sp.

Hence, it can be seen from the preceding paragraphs and from examination of Figure 11 that during the Paleogene a very large area of Papua including most of the central foothills and much of the region to the north was covered by a thin, nearly continuous blanket of a reef-shoal type clastic limestone facies. However, there are areas, especially around the periphery of the clastic limestone realm, where the Paleogene section is comprised of other rock types which imply variations in the general tectono-environmental regime. In the Aure scarp near the junction of the Aure and Purari Rivers Carey (LI, 1941) has described a Paleogene section of at least 370 meters. Although this section includes some units very similar to the clastic limestone suite described above, the bulk of the rocks have a very different lithologic character. One unit of about 75 meters is comprised of "basinal", fine-grained limestones containing Globigerina and Gumbelina. Another unit approximately 30 meters in thickness is comprised of graywacke, marl and grits. Clearly these units differ from the normal Paleogene rocks both in lithology and thickness and were deposited in a rather different tectonic environment. The lithologies seem to suggest deposition in an infraneritic environment on an unstable, subsiding platform or possibly

in a geosynclinal trough. This is in marked contrast to the epineritic, stable platform environment in which the clastic limestones of the central foothills developed.

The Paleogene rocks encountered in the Wana bore are comprised of arenaceous limestones with some argillaceous limestone and siliceous limestone attaining a total thickness of 330 meters. These rocks are also probably more typical of an unstable platform environment of deposition. Tentatively, they might represent part of a generally subsiding hinge zone bordering the eastern margin of the more stable shelf. However, there is some indication that this unstable area extended northwestward from Wana into the stable shelf. This is indicated by both the isopach distribution and the lithologies developed in the Paleogene at Omati and Barikewa. All these localities have argillaceous limestones which might suggest somewhat less stable conditions than was normal for the Paleogene. At Barikewa the Paleogene is represented by about 70 meters of dominantly argillaceous limestone, marly limestone with chert and some mudstone interbedded with minor amounts of the normal shoal limestones. Basinal limestones are present at Omati as has been previously mentioned.

There is also good evidence that this unstable hinge zone extended northward from the Aure-Purari area into the central cordilleran region. In the Asaro River area foraminiferal limestones grade upward into gray shales indicating increasing tectonic instability during the Paleogene. Similar gray shales are associated with Globigerina limestones in the Kami area (McMillan and Malone, 1960) which also points to more unstable conditions of deposition in deeper water than was apparent in the

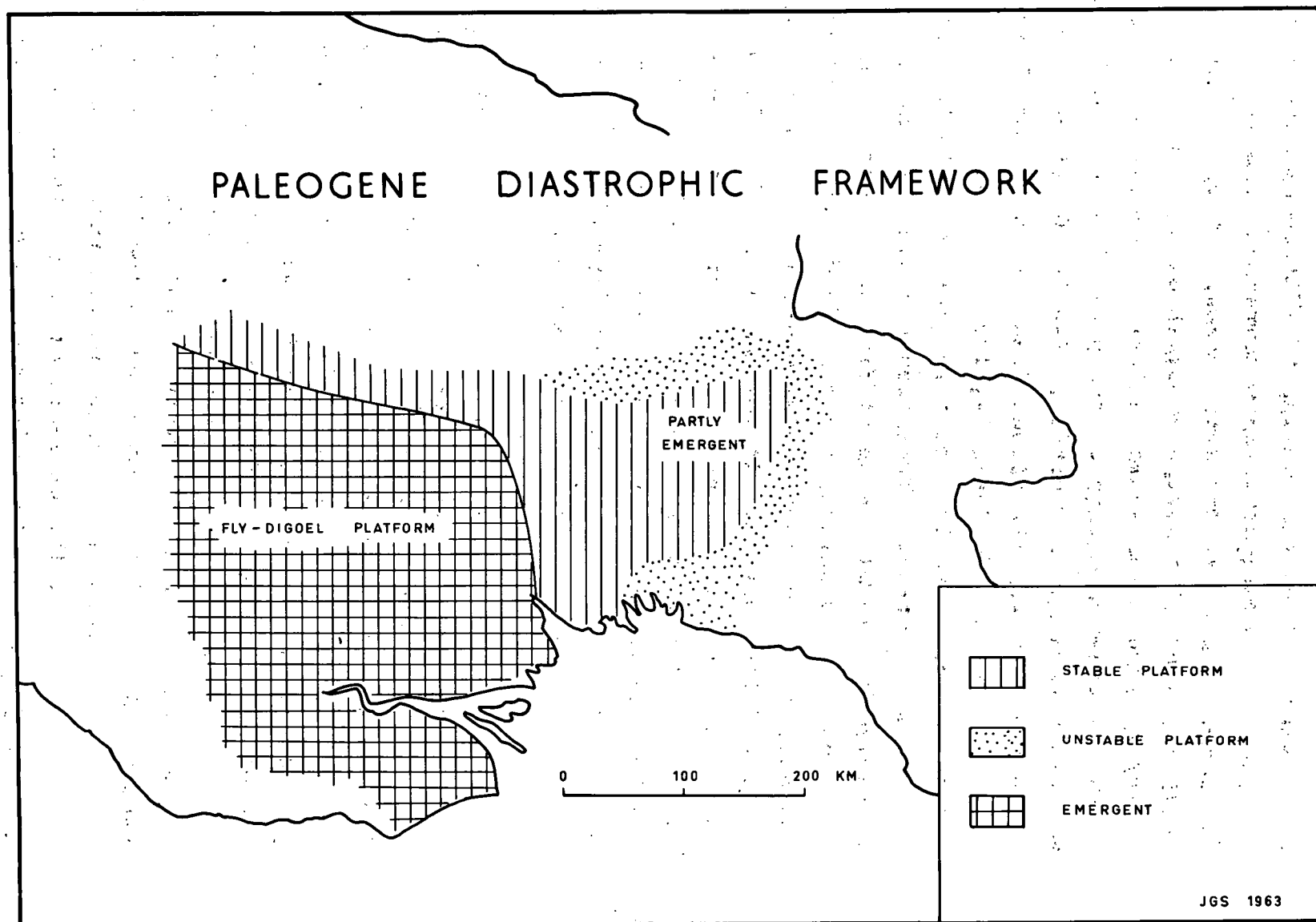
central foothills region.

Another zone of apparent instability forms the northern margin of the Paleogene clastic limestone realm. In the Bundi area (McMillan and Malone, 1960) the Paleogene is represented by about 900 meters of black shale and slate with interbedded sandstones and a few lenses of limestone. Conglomerate beds that contain subangular fragments of quartzite, dolerite and slaty shale are also common. Rickwood (1955) has reported about 300 meters of argillaceous limestones in the Nebilyer Valley. These limestones contain Globigerina sp., Globorotalia sp. and Gumbelina sp., and are apparently deep water sediments. Both these sequences were deposited in a less stable environment than that which existed to the south in the central foothills. However, in the western Bismarck Range, Dow and Dekker (1963) report that some quartz sandstone, calcarenite and conglomerate are associated with the shale and siltstone of the early Lower Miocene to late Cretaceous Asai beds. These former rocks are typical of a relatively stable environment and indicate that the Paleogene shelf may have occasionally extended as far north as the western Bismarck Range.

1.6.2 Paleogene Diastrophic Framework

Platform realm.-- In the preceding pages I have already pointed out that the large majority of Paleogene rocks found in Papua were deposited on a stable platform which was covered by shallow transgressive seas. The areal extent of this platform (Fig. 12) is reasonably well defined in the eastern part of the central foothills but is practically unknown in the westernmost regions of Papua. There are no occurrences of Paleogene rocks in any of the wells which were drilled on the Fly-Digoel shelf (Fig. 10).

Figure 12



It appears certain that during the Paleogene most of this region was an emergent terrain comprised mainly of Cretaceous and other Mesozoic rocks. There is some indication that the northern margin of this emergent platform trended west-northwestward, roughly coinciding with the southern margin of the present main cordillera in western Papua and New Guinea. Nearly 80 meters of Paleogene shallow water limestones found in the Palmer River area (Zehnder and de Caen, JK, 1955) suggest that the Paleogene seas were in fact transgressing onto the shelf from this direction. This transgression is further suggested by the Oligocene affinities of some of the lower units of the New Guinea Limestone Formation (Lower Miocene) which is developed in the Star Mountains. The eastern margin of the emergent platform is reasonably well defined and trended nearly north-south extending from the mouth of the Turama River to near Lake Kutubu. East of this line the bulk of the Paleogene rocks described in the preceding pages were being deposited on a mildly subsiding platform covered by generally transgressive seas.

Although the Paleogene lithologic associations, which were developed in the eastern part of the central foothills in general indicate a stable platform environment, the incomplete and patchy occurrences of these rocks, nevertheless, attest to periodical vertical oscillations of the shelf. In the Pio-Purari region for instance, the distribution of the Paleogene is quite incomplete and in several areas it is completely absent (Kent and Rickwood, LW, 1956). A certain amount of this patchiness can be attributed to removal during the Lower and Middle Miocene when these rocks were exposed in the Erave-Wana swell. However, the presence of fragments of Distichoplax biserialis found in the Paleogene of one area indicates

that deposits as old as lowermost Eocene, possibly Paleocene (?), were being eroded and redeposited in the Upper Eocene or Middle Oligocene. A similar pattern of sedimentation is evident throughout the eastern part of the central foothills region and is typical of a transgressive phase of deposition on a stable platform.

Unstable regions--- It has been pointed out that the lithology of the Paleogene rocks developed in several areas indicates conditions of deposition which were far more unstable than those conditions under which the bulk of the Paleogene rocks developed.

In the first place it is likely that the stable shelf environment of deposition was bounded on the east by a north-south-trending belt where unstable conditions of deposition were thought to have prevailed as indicated by the basinal limestones and graywackes developed in the Aure-Purari area. Such conditions are what one would expect, remembering that this zone was destined to become the site of very thick geosynclinal sedimentation during the Lower and Middle Miocene (Aure trough). However, I hesitate to assign the Paleogene rocks of the Aure-Purari area to a geosynclinal environment but prefer to think of them as having been deposited on a rapidly subsiding shelf. Probably the basinal, argillaceous limestones which Rickwood (1955) reported in the Nebilyer Valley have a similar origin and indicate the presence of a rapidly subsiding zone lying to the north of the platform which extended farther northward at that time than in any subsequent period in the history of the Papuan geosynclinal system. The relatively thick (930 meters) black shale and conglomerate units occurring in the Bundi area suggest that deposition along this northern

zone was approaching geosynclinal conditions but with intermittent periods of stability as evidenced by the calcarenites in the Asai beds. Occurrences of actual geosynclinal rocks are not found in the regions considered in detail by this study. Great thicknesses of agglomerate and limestone occur in the Finisterre Mountains north of the Ramu River and are associated with geosynclinal development in that region (Ongley, GN, 1939).

1.7 CRETACEOUS AND JURASSIC DIASTROPHISM

Cretaceous rocks have a widespread but discontinuous distribution throughout western Papua and New Guinea. Surface exposures are limited to three areas where vertical movements associated with the Plio-Pleistocene orogenesis were apparently at a maximum; namely, the western cordilleran region, the Bismarck and Kubor Ranges of the central cordilleran region and finally in the Erave-Purari area. Additional information concerning Cretaceous rocks has been obtained from drill holes in the Delta embayment and on the Fly-Digoel shelf regions. In general the Cretaceous rocks occurring in these areas correspond to the Neocomian, Aptian, Albian, Cenomanian, Turonian and Senonian Stages of the European Cretaceous. However, in any one locality only a small portion of the total Cretaceous sequence may be present. These discontinuities in the present distribution of the Cretaceous rocks are the result of differential uplift, denudation and erosion which have been nearly continuous phenomena in the development of the New Guinea orogen. There is also evidence to suggest that Cretaceous rocks may have been subjected to regional metamorphism in some areas, a possibility which further complicates the study and analysis of the original pattern and diastrophic environment of Cretaceous sedimentation. However, it can be shown that there were two main tectonic environments of deposition during the Cretaceous: a geosynclinal

belt and a platform realm. Furthermore, it is possible to recognize two stages in the development of these environments which will be referred to as a late Cretaceous stage (Cenomanian, Turonian, and Senonian) and an early Cretaceous stage (Neocomian, Aptian, and Albian).

The oldest system of sedimentary rocks having regional importance in Papua and New Guinea are Jurassic. These rocks outcrop both in the central and western cordilleran regions and comprise a suite of geosynclinal rocks including shales, siltstones and sandstones. A similar sequence of rocks has been revealed by drilling in the Delta embayment. However, on the Fly-Digoel shelf in southwestern Papua drilling has revealed a Jurassic series of arkosic and argillaceous sandstones associated with carbonaceous mudstones and coal, which in contrast to the above rocks are likely to have formed on a slowly subsiding shelf. Hence, as was the case in the Cretaceous, Jurassic sedimentation was controlled by a diastrophic framework consisting of a mobile geosynclinal belt that formed the northern margin of a broad platform which coincided very closely with the present extent of the Fly-Digoel shelf.

1.7.1 Late Cretaceous

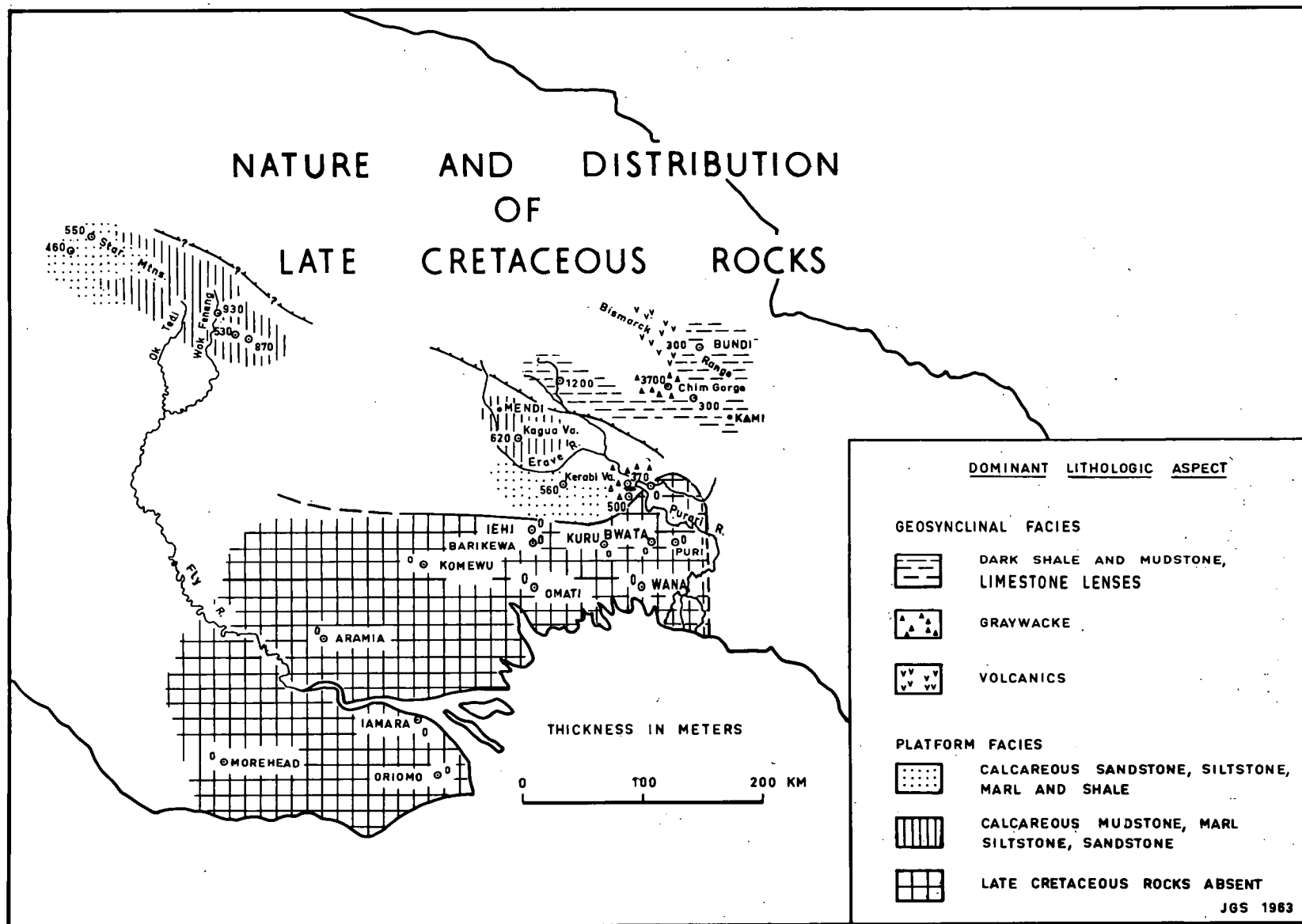
Late Cretaceous rocks accumulated in two main tectonic environments. The relatively thick rocks occurring in the central cordilleran region are indicative of geosynclinal conditions of accumulation and are accompanied by some volcanics. An unstable platform environment is indicated by the lithologic assemblages mapped in two widely separated areas, the western cordilleran region and the Erave-Purari region. Wells drilled in the Delta

embayment and on the Fly-Digoel shelf passed directly from Tertiary rocks into early Cretaceous rocks demonstrating the absence of late Cretaceous rocks in those regions. The scattered and incomplete nature of the late Cretaceous rocks has made it nearly impossible to define the limits and relations of the two main diastrophic environments of sedimentation. The same conditions also make it almost impossible to draw reliable isopachs. Hence, on Figure 13 I have shown only the lithology and thickness of late Cretaceous rocks and the very general extent of the tectonic environments which have been postulated on the basis of the lithologic assemblages.

Geosynclinal zone.-- Late Cretaceous rocks occurring in the central cordilleran region of New Guinea are a typical geosynclinal assemblage. Upper Cretaceous rocks mapped by Rickwood (1955) in the Chim Valley total 3700 meters, although it is possible the lower part of this sequence may be early Cretaceous. These rocks (Chim Group) consist of shales, graywackes and tuffaceous mudstones. The upper beds of this series is generally coarser than the lower beds and contain conglomerate and shelly layers which led Rickwood to suggest a gradual shallowing of the late Cretaceous seas in the Chimbu area. An olivine basalt also occurs near the top of the section in the Chim Gorge. To the west in the Nebilyer Valley, Rickwood found the Upper Cretaceous to be represented by a considerably thinner (1200 meters) sequence of thin-bedded shales that are calcareous near the top.

Recent unpublished information gathered in the western Bismarck Range for the Bureau of Mineral Resources by D.B.Dow and F.E.Dekker (1963) indicated the presence of an Upper Cretaceous sequence comprised mainly of basaltic

Figure 13



marine volcanics with some associated sediments. Furthermore, they recognized a Middle Cretaceous section consisting of silts and shale in the upper half and prominent graywackes in the lower half. For the purpose of this study I have split this unit and have placed the upper silts and shales with the late Cretaceous and the graywackes with the early Cretaceous. From a tectonic point of view such a subdivision of the so-called Middle Cretaceous beds will be consistent with the other early and late Cretaceous lithologic sequences developed elsewhere in the central cordillera.

The mapping of Dow and Dekker has also revealed the presence of a shale, siltstone, phyllite and schist sequence on the western end of the Bismarck Range which may include late Cretaceous and even lower Tertiary rocks (Asai beds).

In the Eastern Central Highlands of New Guinea McMillan and Malone (1960) have reported Upper Cretaceous rocks which are typical of geosynclinal accumulations but which have a thickness considerably less (300 meters) than that of the Chim Group to the west. For example in the Watabung area, 30 kilometers northwest of Kami, Upper Cretaceous rocks include light gray mudstone, gray shale with lenses of fine-grained limestone. The maximum thickness has been estimated at 300 meters but it is likely that the original thickness was somewhat greater. Similar fault-bounded blocks of Upper Cretaceous rocks are also reported at Bundi and Kami. On the basis of foraminifera including Pseudorbitoides sp. and other forms Crespin and Belford (1957) refer the rocks to the Upper Senonian. McMillan and Malone point out that these rocks do not appear to have any equivalent in the Chim

Group and point to the similarity in age to marls occurring in the Mendi area.

Hence, the central cordilleran region was the site of geosynclinal deposition during the late Cretaceous. However, the coarsening of the Chim Group toward the top of the section and the development of thinner limestone sections in the Eastern Central Highlands suggest the beginning of a phase of geosynclinal stabilization in the latest Cretaceous, which as we have seen was fully developed in the central cordillera during the Paleogene.

Platform realm.-- Late Cretaceous rocks developed in the western cordilleran region and the Erave and Purari Rivers region indicate an unstable platform or shelf environment. In the Wok Feneng, a tributary of the Fly River, Osborne (1945) reported 930 meters of Cenomanian and Turonian rocks (Feing Group). They consist of calcareous mudstones, micaceous siltstones and sandstone and containing Inoceramus sp. and abundant microfossils. Similar sections of late Cretaceous rocks are found in other tributaries of the Fly River such as the Ok Tedi, Wok Luap and Wok Tungom.

To the west in the Star Mountains region the upper part of the Kembelangen Formation is thought by Bär et al. (1961) to be Upper Cretaceous. In the Awitago area these rocks are 125 meters thick and consist predominantly of calcareous sandstones, siltstones, marls and shales. Glauconite is common. In general, this assemblage would indicate an unstable shelf diastrophic environment. However, there are several units of clean well-sorted orthoquartzite sandstones and quartzitic sandstones which are typical of a more stable platform environment and thus

indicates periodic fluctuations between the two diastrophic regimes.

As is evident on Figure 13 the western cordilleran platform region is isolated from the other areas of Upper Cretaceous information, and it is difficult to see how the rocks in this region fit into the gross pattern of late Cretaceous diastrophism. It is especially interesting to consider the possibility of Cretaceous rocks extending northward from this region. In the Upper Sepik area lower Tertiary rocks are observed to rest directly on metamorphic basement (S.J.Paterson, pers.comm.). On the other hand, sandstones reported by Behrmann (1917) on the north side of the main cordillera between the April and Upper Sepik Rivers are thought to be Mesozoic (David, 1950, p.669) and may possibly be Cretaceous.

It may be possible that the metamorphic basement rocks exposed in the Upper Sepik River represent a portion of a positive tectonic block which was emergent during the Cretaceous. Another possibility is that the metamorphics are themselves composed of Cretaceous rocks. The problem will be resolved only by more field work in the mountainous regions of western New Guinea.

A very similar lithologic association, which is thought to represent an unstable shelf association, occurs in the eastern part of the central foothills belt. In the Kagua Valley south of Mount Giluwe, about 620 meters of Upper Cretaceous (Senonian and Turonian) rocks are developed in a marl, shale, siltstone and sandstone facies. The top 300 meters of this section is comprised of marls containing Upper Senonian foraminifera. Rickwood

(1955) reported a similar sequence of marl near Mendi which he called the Mango Marls. A particularly interesting sandstone unit forms the lower 80 meters of the Kagua Valley section. The sand consists of quartz, biotite, hornblende, plagioclase and very small grains of metamorphic rocks. This occurrence, as well as many of the highly quartzose layers in the Star Mountains area, suggests that crystalline rocks of acid to intermediate composition were shedding sediment during the Cretaceous.

To the south in the Kerabi Valley area the late Cretaceous is represented by fine and medium sandstones with occasional mudstone bands in the lower part. South of Lake Tebera the late Cretaceous consists of 500 meters of Cenomanian "greensands" consisting of angular quartz, feldspar and glauconite with subordinate amounts of hornblende, chlorite and biotite. On the north side of Lake Tebera 370 meters of thick-bedded, green graywackes of Cenomanian age are exposed. This latter occurrence suggests that perhaps periodic geosynclinal incursions took place on this portion of the shelf.

Exploratory bores at Iehi, Barikewa, Omati, Puri, Wana and Kuru in the Delta embayment region and at Aramia, Komewu, Oriomo and most recently at Iamara in southwestern Papua passed from Tertiary rocks directly into early Cretaceous rocks and define a very large area where late Cretaceous rocks are absent. There is some possibility that 700 meters of alternating sandstone and mudstone at Morehead are Cenomanian which would alter the outline of the emergent area represented on Figure 13.

The absence of late Cretaceous rocks in the Fly-Digoel shelf and Delta embayment regions is most likely

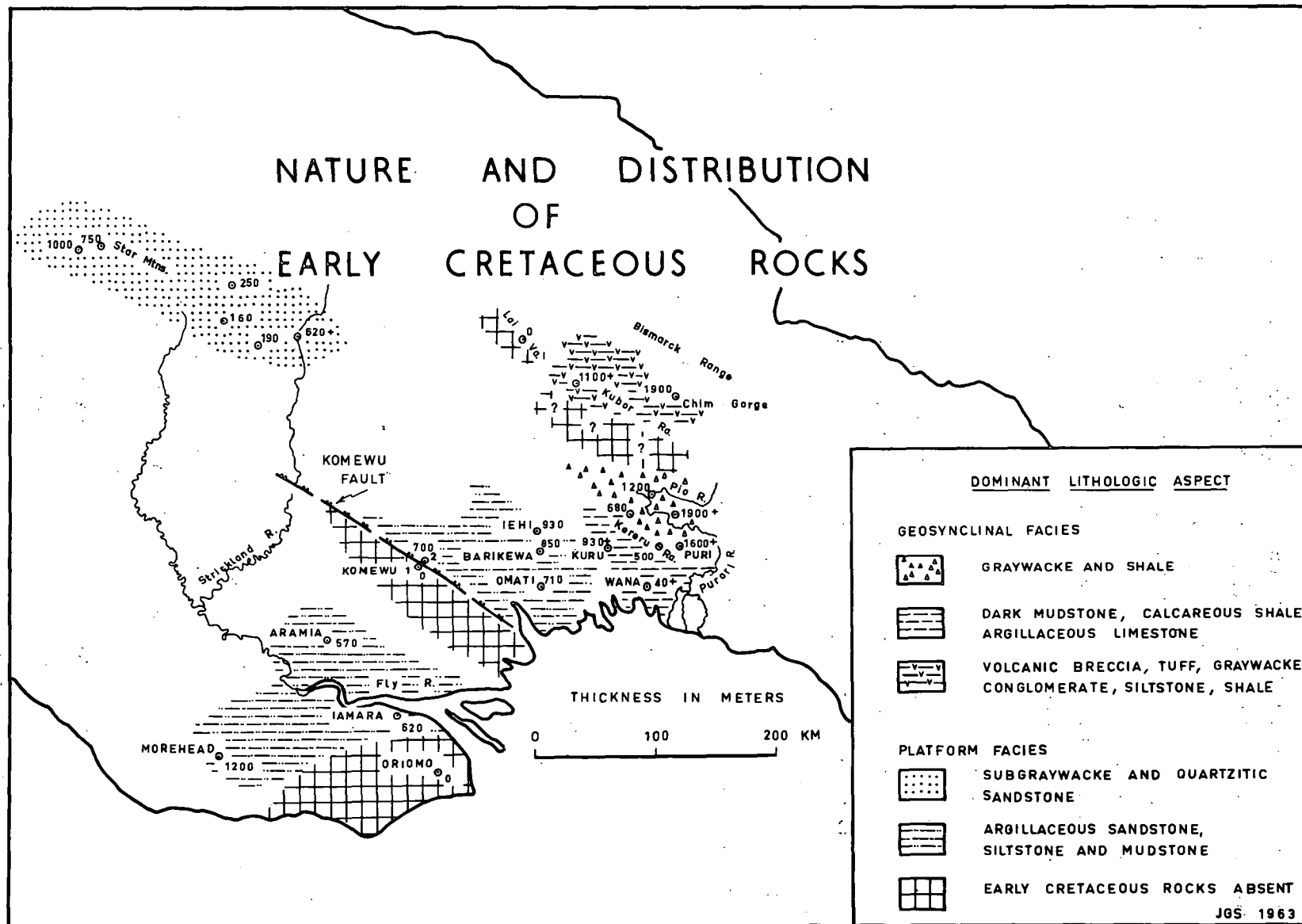
due to subsequent emergence and erosion. Certainly during the Paleogene most of this region, especially the Fly-Digoel shelf region, was clearly emergent and any late Cretaceous rocks which might have been present were probably eroded. Such erosion is suggested by the occurrence of pebbles of presumably Cretaceous siltstones in the Paleogene rocks of the Kereru Range (Section 1.6.1).

1.7.2 Early Cretaceous

The diastrophic framework of the early Cretaceous sedimentation is similar to the late Cretaceous in that two main tectonic regimes of sedimentation can be recognized: a geosynclinal zone and a platform regime (Fig.14). The geosynclinal zone is again confined to the central cordilleran and Pio-Purari River regions. Lithologic assemblages of the platform type are far more extensive than were their late Cretaceous counterparts. The distribution of early Cretaceous rocks in southwestern Papua indicates the presence of important faulting which probably took place during the late Cretaceous or Paleogene.

Geosynclinal zone.-- Early Cretaceous geosynclinal sediments outcrop both in the Kubor and Bismarck Ranges of the central cordillera and in the Pio-Purari River area of the central foothills region. In the Chim Valley Rickwood (1955) found the Lower Cretaceous to consist of about 1900 meters of well-bedded volcanic breccia, tuff, conglomerate, graywacke, siltstone and shale (Kondaku Tuffs). The more volcanic units of this sequence generally occur near the base. For instance near Kuta on the western end of the Kubor Range, where 1100 meters of the Kondaku Tuffs are exposed, the andesitic tuffs are confined to the lower 600 meters.

Figure 14



The upper part consists of dark gray shales and fine graywackes with some black, fine-grained pyritic limestone. In some areas on the north side of the Kubor Range a tuffaceous conglomerate occurs with boulders up to two-thirds of a meter in diameter consisting of basic lavas and occasional metamorphic pebbles in a silty matrix. Vesicular basalts, associated with boulders of basalt in a tuffaceous matrix, form the base of the early Cretaceous near Mingende. Early Cretaceous rocks are absent west of the Mount Hagen Range in the Lai Valley where late Cretaceous rocks rest directly on Paleozoic (?) plutonic rocks.

A suite of early Cretaceous geosynclinal graywackes is also developed in the Pio-Purari area. Carey (1945) reported 1600+ meters (Purari Formation) of massive to thick-bedded graywackes and dark, thin-bedded mudstones of Aptian to Albian age. Edwards (1950a) made a petrologic study of these rocks. He found them to consist essentially of

... angular grains of quartz and feldspars of various types, with lesser amounts of hornblende, chlorite, biotite, leucoxene, iron ores, glauconite and minor accessory minerals, together with numerous fragments of sedimentary and igneous rocks, set in a prominent fine-grained argillaceous and chloritic matrix. The texture could be described as that of a micro-breccia.

On the evidence of the rock fragments, Edwards felt that some of the Purari graywackes were derived in part from sedimentary schists and mudstones, and in part from andesitic tuffs or related rocks. However, the bulk of the rocks, excluding the matrix, consists of grains of clear quartz, orthoclase and acid plagioclase, and in all probability the chief source rocks were granitic in

character. The chemical composition of the Purari rocks also supports this conclusion. Edwards considered that the occurrence of fossiliferous marine shell bands, beds with plant remains, such as Sphenopteris, and grains of glauconite indicate that the sediments were deposited under marine conditions close to a coastline. He also felt that the source of the detritus was exposed to rapid and vigorous erosion and the derived materials were discharged into still and relatively deep water but within the limits of the neritic zone.

The lateral extent of the geosynclinal realm indicated by the lithologic associations in the Pio-Purari area and in the central cordillera is unknown. It is quite likely that the geosynclinal deposits in these two areas were not part of the same basin but were separated by a geanticlinal ridge. This ridge was probably developed in crystalline basement rocks and would serve as a source for the Purari graywackes described above. It is quite unlikely that these rocks were derived from a source to the south. As we shall see the area to the south of the Purari region was the site of deposition rather than erosion in the early Cretaceous.

It is interesting to note that in the Snake River Graywacke, a member of the Kaindi Metamorphic Group in the Morobe district (Fisher, 1944), M.F. Glaessner (1949) identified a fauna of Lamellibranchia which indicate an Aptian to Albian or Cenomanian age. The lithology of the rocks is very similar to the Purari Formation and it is possible that these rocks are part of the same geosynclinal system. The fact that these rocks have been metamorphosed to some extent opens the possibility that the absence of Cretaceous and other Mesozoic rocks in some

areas of the cordilleran belt may be due to metamorphism. This may especially apply to the western cordilleran region where one would normally expect to find some traces of the westward extension of the early Cretaceous geosynclinal belt. The possibility of metamorphism of late Cretaceous rocks in this region has already been suggested.

In the Kereru Range about 500 meters of disturbed, calcareous shale containing frequent calcareous concretions are found (Tubu Shales; J.P. de Verteuil and R. McWhae, LQ, 1948). The age of these beds is very much in doubt but is generally thought to be Upper Jurassic to Lower Cretaceous. At least 1600+ meters of similar rocks were encountered in the Puri well which consisted of silty, dark gray mudstones with concretions of dark argillaceous limestone and glauconitic argillaceous siltstone. These are regarded generally as Lower Cretaceous. Similar rocks were also encountered in the Kuru and Wana bores. It appears that these rocks occur in a position transitional between the graywackes of the Pio-Purari area and the sandstone-siltstone facies developed to the southwest in a platform environment.

Platform realm.-- Early Cretaceous lithologic associations indicative of a platform tectonic environment are known to occur in two regions: the western cordilleran region and the eastern part of the Fly-Digoel shelf. According to Bär et al. (1961) the early Cretaceous rocks of the Star Mountains region are represented by about 1000 meters of argillaceous, micaceous subgraywacke-type sandstones and siltstones. Included in the sequence are some orthoquartzite sandstones and also shales and claystones. The bottom of the sequence is formed by a conglomerate between 55 and 250 meters in thickness

consisting of cobbles of quartz and shale pebbles. Bär concluded that deposition of these rocks occurred on a shallow, slowly subsiding shelf.

Similar lithologies; namely, argillaceous, glauconitic sandstone with white quartzitic sandstones, occur in the headwaters region of the Fly and Strickland Rivers and are indicative of a similar environment of deposition.

To the southeast 700 to 930 meters of early Cretaceous rocks were revealed in the Iehi, Barikewa and Omati bores. These rocks consist dominantly of argillaceous sandstone with some glauconitic sandstone, mudstone and siltstone, and attest to a platform environment of deposition, but with a greater degree of stability than is likely to have existed during the early Cretaceous in the Star Mountains region. A similar lithologic assemblage, 700 meters in thickness with a rich foraminiferal fossil fauna, was encountered in the Komewu No.2 bore. However, in the Komewu No.1 bore about two kilometers to the southwest, no early Cretaceous rocks were found and the Lower Miocene rocks rest directly on Upper or Middle Jurassic. This relationship confirmed the presence of a large fault (Komewu fault) which was originally detected by seismic work. South of the Komewu fault early Cretaceous rocks are found in the Aramia, Iamara and Morehead bores and, again, are represented by a dominantly argillaceous sandstone sequence with alternating layers of mudstone and siltstone ranging between 550 and 650 meters in thickness. This facies is typical of deposition on a mildly unstable platform.

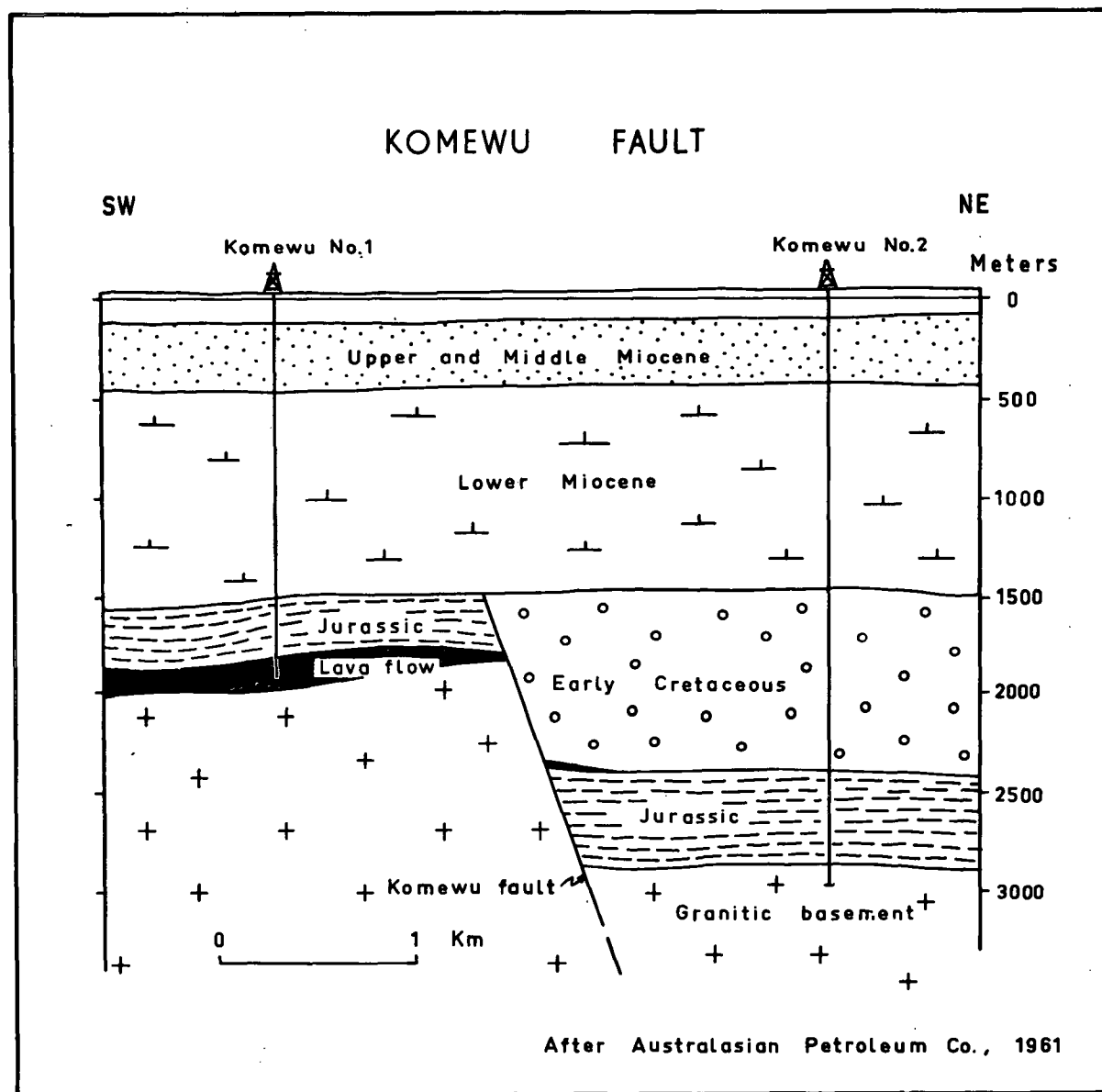
The orientation and extent of the Komewu fault as shown on Figure 14 is based on a study made by Malone (XCA, 1955) of magnetic and seismic information in southwestern Papua. The fault has been represented diagrammatically as a continuous zone. In reality it is probably a complex series of discontinuous fractures possibly arranged in an en échelon pattern. Vertical displacement along the fault at Komewu has been about 1200 meters (Fig. 15) and the seismic information suggests even greater displacement to the southeast. As yet there is no evidence for lateral movement along the fault.

In view of stratigraphic relations both in the Komewu wells and at other localities in southwestern Papua it is possible to somewhat restrict the age of the faulting. Lower Miocene rocks pass over the fault zone without any apparent interruption indicating pre-Lower Miocene movement. The very continuous and homogeneous nature of the early Cretaceous argillaceous sandstone facies in southwestern Papua, as well as the lack of conglomerates and other coarse clastics in the Komewu No. 2 bore, suggests that faulting had little or no control on early Cretaceous sedimentation. Hence, it is likely that all the movement was restricted to the uppermost Cretaceous and Paleogene. The tectonic significance of the Komewu fault will be examined in several subsequent sections.

1.7.3 Jurassic

Platform realm.-- All drill holes in southwestern Papua passed through Jurassic rocks before bottoming in crystalline basement rocks (Fig. 16). The lithology and

Figure 15

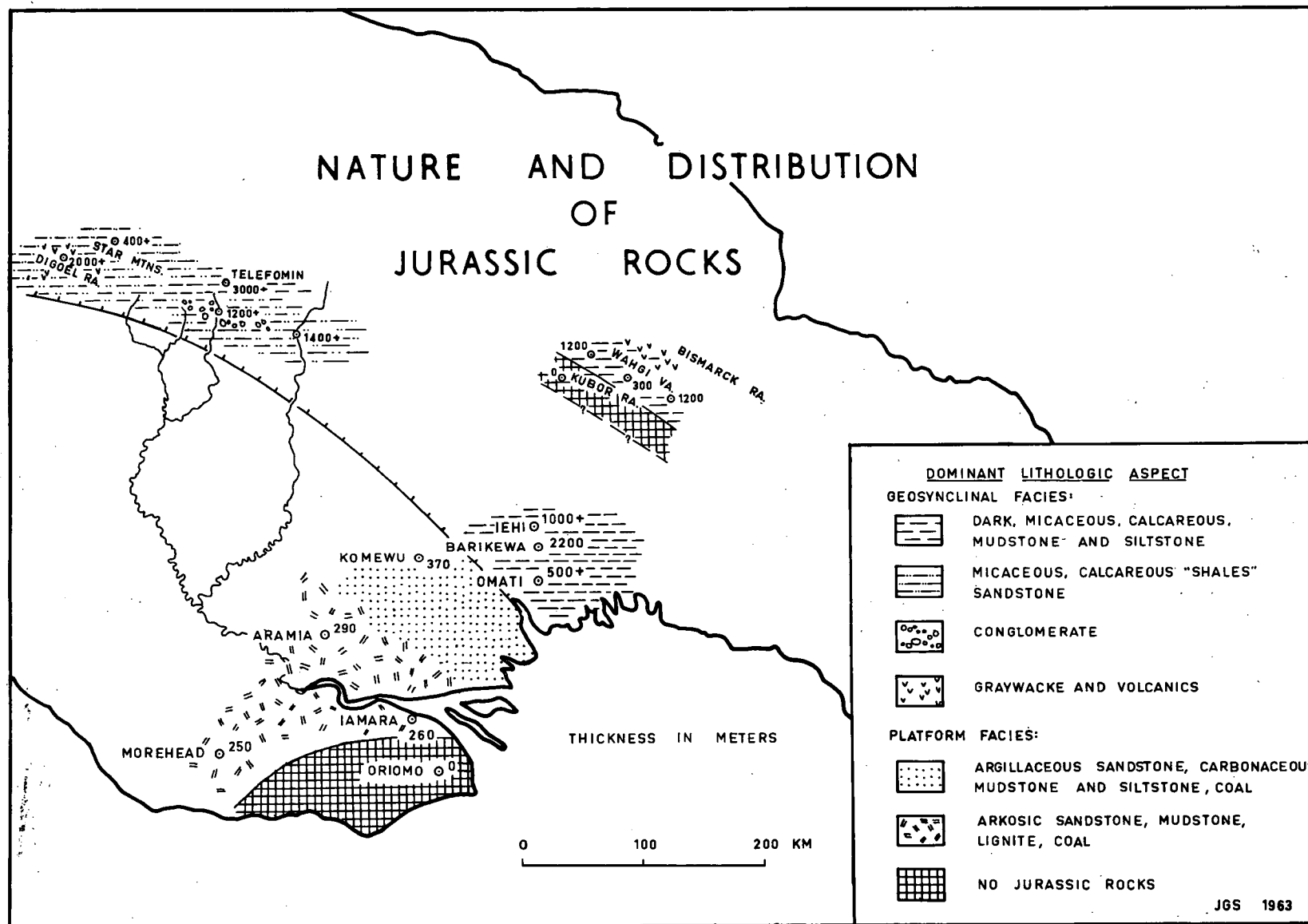


thickness of the rocks encountered in these bores indicated a southwest to northeast transition from shallow water to deeper marine conditions of platform deposition. In the Morehead bore, which was drilled on the Oriomo Plateau, the Jurassic section consisted of 250 meters of microcrystallized arkosic sandstones containing minor bands of lignite near the base. The bore did not penetrate the underlying crystalline basement which was indicated by seismic velocity work to be situated at a depth of 65 meters beneath the base of the bore. Two hundred and sixty meters of Jurassic rocks were recently encountered in the Iamara No.1 well at the mouth of the Fly River. As yet there is no lithologic information from this site. The Mesozoic section in the Oriomo bores is very thin and some of the lower bituminous gray shales and kaolin may be of Jurassic age.

In the Aramia bore the Jurassic sequence consists of an upper unit of silty mudstone with an assemblage of Upper Jurassic belemnites and lamellibranchs (125 meters). Underlying these beds is a series of arkosic sandstones, thin carbonaceous shales and high-grade coal beds that represent a Lower Jurassic transgressive facies across the underlying granitic basement. The Jurassic rocks in the Komewu bores, consisting primarily of argillaceous sandstones with mudstones, siltstones and basal coal units, are also typical of the transgressive platform facies.

Geosynclinal zone.-- In contrast to the rocks in the Aramia-Morehead area, which represent a transgressive shelf environment, the Jurassic rocks encountered in the Barikewa, Iehi, and Omati wells are more typical of geosynclinal marine sedimentation. Barikewa the 2200 meters of Jurassic rocks consist mainly of dark, slightly

Figure 16



pyritic micaceous and silty mudstones with some siltstones as well as silty and calcareous sandstones. The rocks in both the Omati and Iehi wells are quite similar and consist of mudstones, siltstones and fine sandstones that are sometimes calcareous and micaceous. It is possible, as has been pointed out in the Cretaceous discussion, that the dark calcareous shales in the Kuru, Puri and Wana wells may have some Jurassic affinities. In any event these rocks fit equally well into either the Upper Cretaceous or Jurassic diastrophic framework.

Jurassic rocks of the central cordilleran region are also developed in a geosynclinal facies. The large majority of these rocks outcrop along the northern edge of the Kubor Range in the Wahgi Valley and were described by Rickwood in 1955. They consist of a series of dark silty shales (Maril Shales) and associated coralline limestones that are 1200 meters thick in the Wahgi Gorge. The Jurassic sequence thins to the west and finally wedges out between the Cretaceous rocks and the crystalline basement on the westernmost end of the Kubor Range, which was apparently positive during the Jurassic. This shale-limestone facies is transgressive onto the older Permian and crystalline rocks forming the core of the Kubor Range. The coralline limestone lenses, containing Thamnasteria sp., Stylina sp., are interpreted by Rickwood to be the remnants of fringing reefs which developed along the side of the Jurassic ancestor of the Kubor Range. The shales contain Inoceramus fragments, sponge spicules and radiolaria.

In the western Bismarck Range Dow and Dekker (1963) have reported that these shales are underlain by older Jurassic rocks of geosynclinal character. They recognize

two older units: a Middle Jurassic unit comprised of basic marine volcanics and conglomerate; and a Lower Jurassic unit consisting of graywackes and siltstones.

Jurassic rocks of a geosynclinal facies are also present in the western cordilleran region. The 3000 meters of black, micaceous shales found at Telefomin are somewhat reminiscent of the shale facies of the Wahgi Valley and Barikewa. Elsewhere in the western cordillera, the Jurassic sections contain considerably more sand and silt size material. For instance the Upper Jurassic section (Kubagen Group) in the Wok Feneng, that was described by Osborne (1945), consists of 1200 meters with micaceous, calcareous and silty shales, argillaceous sandstones with some "greensands" and orthoquartzite sandstone. The basal unit of this sequence is particularly significant. It consists of 280 meters of conglomerates containing subangular pebbles and boulders up to 20 centimeters in diameter of coarse pink granite in a matrix of purple argillaceous sandstone. This occurrence indicates that there was considerable relief developed in the pre-Jurassic crystalline rocks which rimmed the southern margin of the trough. This relief was probably controlled by a fault or a series of faults which separated the platform to the south from the more mobile belt to the north.

Two other partial Jurassic sections described in the upper Strickland region; viz., in the Strickland Gorge (1400 meters) and Wok Tungom (550 meters), consist of interbedded sandstone, siltstone and shales.

Bär et al. (1961) described similar rocks in the Tennam River area of the Star Mountains (Bon Formation).

This section (400+ meters) consists of calcareous sandstones, alternating with siltstones, claystones and dolomitic claystones. Mica and pyrite are a common constituent of these slightly indurated rocks.

According to Bär Jurassic rocks do not occur in the Digoel Range where Cretaceous rocks are said to overlie, with angular unconformity, the rocks of the Kariem Formation which consists of highly indurated, unfossiliferous, calcareous slates, phyllitic slates, and subordinate quartzitic sandstones. On a lithologic basis Bär tentatively correlated these rocks (Kariem Formation) with the Upper Cambrian of northern Australia (Georgina Series). I suggest, however, that these rocks could equally well be a more indurated phase of the Jurassic Bon Formation. Certainly the lithologies of the rocks in question are consistent with this suggestion; i.e., the quartzitic sandstones and micaceous, calcareous shales of the Bon Formation versus the calcareous slates, phyllitic slates and subordinate quartzitic sandstones of the "Paleozoic" Kariem Formation. Comparing other similarities of the Kariem Formation and the Georgina Series, Bär points out that both sequences are intruded by a diorite sill. Finally Bär noted that the Kariem Formation is underlain by a sequence of basic igneous rocks including basalt, gabbro, diabase associated with altered limestones (Awitagh Formation). However, similar basic rocks have been assigned to the Lower Jurassic by Dow and Dekker (1963) in the western Bismarck Range. If these "Paleozoic" rocks; i.e., the Kariem and Awitagh Formations, were indeed Jurassic as I suggest, it would represent a thickness of greater than 2000 meters in the Digoel Range. Both the lithology and thickness of these rocks would be entirely consistent with the

Jurassic diastrophic framework of sedimentation as it can be reconstructed in other regions.

1.7.4 Cretaceous and Jurassic Diastrophic Framework

The main diastrophic elements that persisted throughout the Cretaceous and Jurassic development of western Papua and New Guinea are illustrated on Figure 17; my best estimate of the extent and configuration of the Mesozoic Papuan geosynclinal system. The reconstruction is, of course, based on tenuous and sparse stratigraphic information. Nevertheless, the nature and lithology of the sediments clearly indicate that the Mesozoic was a period of vigorous diastrophism. Consequently the tectonic elements which were developed at that time would be likely to have a strong effect on the subsequent evolution of the geosynclinal system. This possibility justifies the generalized reconstruction of the Mesozoic geosynclinal system that has been prepared.

Fly-Digoel platform.-- As in the Tertiary, platform conditions of deposition persisted throughout the Mesozoic development of southwestern Papua. Very little is known about the structural framework of the platform because the information concerning the Mesozoic in this region comes from a few widely scattered bores. Nevertheless, a few broad and ill-defined structures can be recognized. For instance, the very thin Mesozoic section encountered in the Oriomo bores suggests that the eastern end of the Oriomo Plateau was a structural high. This feature, called the Oriomo spur, is often thought to be a continuation of the northerly structural trends occurring in the Cape York Peninsula. The thicker section (1500 meters) encountered in the Morehead No.1 bore is thought to be

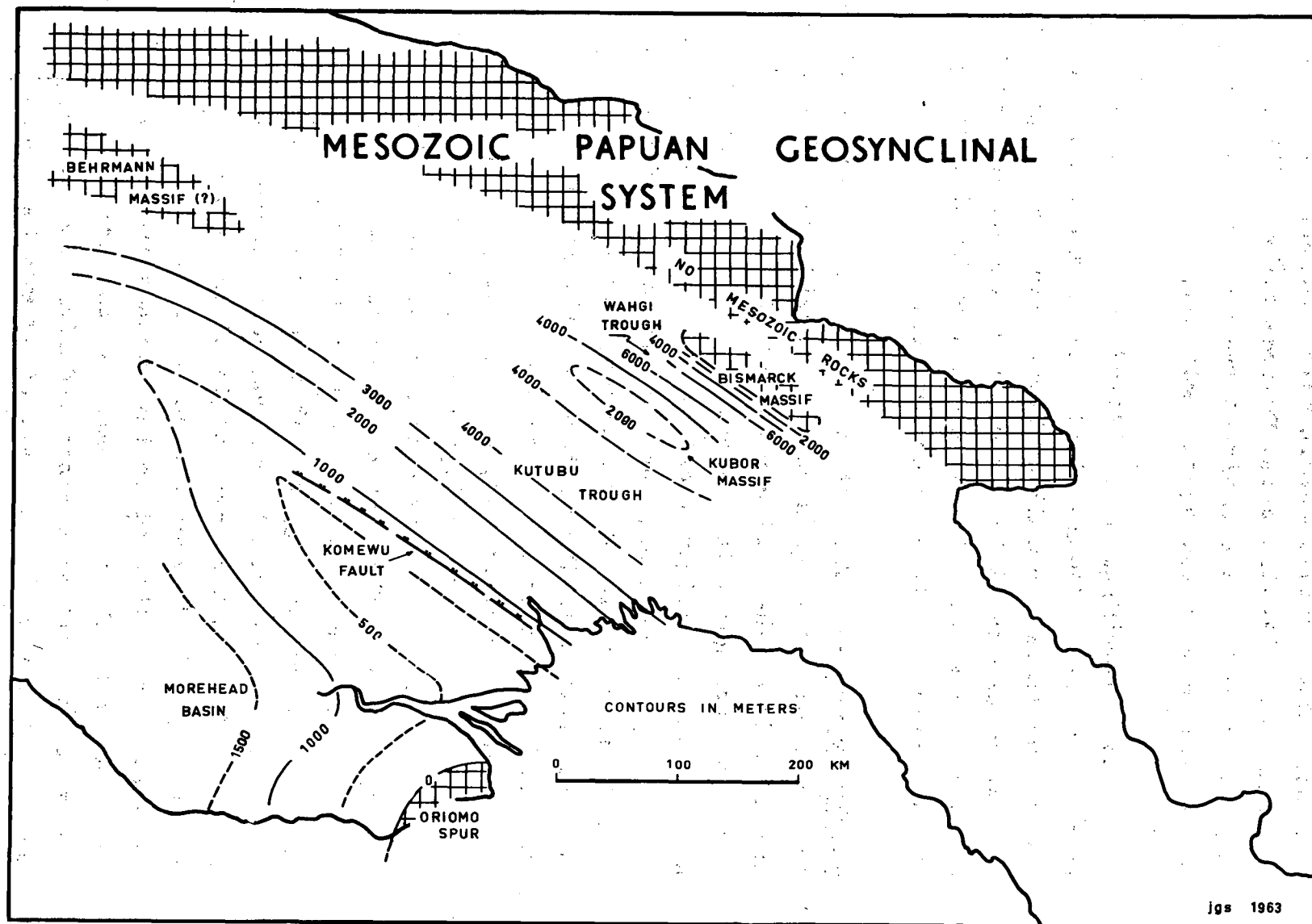


Figure 17

part of a broad shallow basin which has been called the Morehead basin (Australasian Petroleum Co., 1961). The regional extent of these structures has been defined by both seismic and aeromagnetic methods.

Comparing Figures 13, 14 and 16, it is interesting to note that the Fly-Digoel platform, particularly in the regions north of the Gulf of Papua, migrated progressively northward throughout the Mesozoic at the expense of the geosynclinal zone. I will deal with the significance of this migration in a later section.

Kutubu trough.-- The Kutubu trough is the term applied to a zone of active geosynclinal subsidence and deposition which bordered the northern margin of the Fly-Digoel platform throughout the Mesozoic. There is very little known about the original extent and tectonic character of this trough. However, the considerable thickness and lithologic character of the rocks, particularly the Jurassic rocks, in the western cordillera and in the Barikewa and Purari areas strongly suggest that it was a first-order structure and, consequently, was likely to have had a considerable impact on the pattern and nature of the subsequent diastrophic development of the geosynclinal system. The combined thickness and facies information from the Barikewa area and the western cordilleran region suggests that the main trend of the trough was northwesterly and connected these two localities. The southwestern margin of the trough is relatively well defined and on the basis of facies distribution it is thought to have been situated somewhere between the Barikewa and Komewu areas during the Jurassic and somewhat farther northeast during the early Cretaceous. The important Jurassic conglomerate units found in

the headwaters region of the Fly and Strickland Rivers suggest that the edge of the trough was not far to the southwest. These conglomerates also suggest, as I have already pointed out, that the trough was probably separated from the platform by a system of faults. The position of the northeastern margin of the trough is not known but it must be situated somewhere between the Barikewa area and the Kubor massif to the northeast. This is based on the assumption that the massif was positive, although not necessarily emergent, during the Mesozoic. This assumption is substantiated first by the absence of Jurassic rocks in several localities along the core of the Kubor Range, notably at Kuta near Mt. Hagen. Secondly, by the presence of reef-type limestones in the Jurassic rocks and finally by the presence of minerals in the Cretaceous graywackes in the Purari region, which were presumably derived from a crystalline terrain; i.e., the Kubor massif.

Another still more difficult problem concerns the southeastern extent of the trough. Australasian Petroleum Company geologists (1961, Fig.9) have suggested that the trough shallows rapidly from the western cordilleran region southwestward toward the Omati-Barikewa area. I see no evidence for this interpretation and prefer to let the contours open (Fig.17), thus implying that the Kutubu trough may perhaps extend under the northerly-trending Aure trough and into eastern Papua. I have already pointed out the similarity of some of the Cretaceous graywackes in the Purari region with those of the Kaindi Series in the Morobe district.

Cordilleran trough.-- The very thick (7000+ meters) Mesozoic accumulations occurring in the central

cordilleran region are indicative of vigorous geosynclinal subsidence and volcanism. This eugeosynclinal zone will be referred to as the cordilleran trough. In detail it is possible that this trough was split by the Bismarck massif which, like the Kubor massif, is likely to have been positive during the Mesozoic. The positive nature of the former structure is postulated on two lines of evidence. In the first place Lower Miocene rocks rest unconformably on the Paleozoic crystalline rocks which form the core of the Bismarck Range. The minor, isolated remnants of Upper Cretaceous rocks found around the margins of the eastern Bismarck Range; viz., at Watabung, Kami and Bundi appear to represent the initial sedimentation in that area (McMillan and Malone, 1960). In the second place, the Kubor massif has been shown to have been positive during the Mesozoic particularly in the Jurassic and early Cretaceous. On the basis of the very similar nature of these two regions, a fact which will become more evident in later sections of this dissertation, it is suggested that the crystalline core of the Bismarck Range may have also been positive throughout the Mesozoic. The portion of the main cordilleran trough situated between the Bismarck and Kubor massifs will be referred to as the Wahgi trough; the region to the northwest and north of the Bismarck crystalline massif will be called the Ramu trough.

The lateral extent of the cordilleran trough is a matter of speculation, but the scant information available does permit some inferences to be made as to its original configuration. Mesozoic rocks are not known to occur in the northern ranges of New Guinea where Tertiary rocks rest directly on metamorphic and igneous rocks of presumably pre-Mesozoic age (David, 1950). I prefer to think

that this area was positive during the Mesozoic and formed the northern margin of the Papuan geosynclinal system. There is no evidence to substantiate this assumption and Mesozoic rocks could have been deposited here and eroded prior to the deposition of the Tertiary. However, this is thought to be unlikely and, as I have just pointed out in reference to the Bismarck massif, we shall see that the overall evolution of the geosynclinal system suggests that both these regions were positive during the Mesozoic.

West of the central cordilleran region the width of the Mesozoic geosynclinal belt is considerably reduced. In fact, the Kutubu and cordilleran troughs converge in the western cordilleran region. The relative intensity of diastrophism also appears to decrease in that direction as well. This is witnessed by the fact that the Mesozoic rocks developed in the western cordilleran region are more typical of miogeosynclinal deposits or may even have been deposited on a rapidly subsiding platform. Geosynclinal sinking and deposition certainly was not accompanied by the amount of volcanism evident in the central cordilleran region. The basalts of the Jurassic (?) Awitagh Formation are a possible exception to this generality.

Again by analogy with the central cordilleran crystalline massifs; it is possible that the metamorphic rocks, which form the core of the western cordillera, may have been positive through at least part of the Mesozoic. The structural character of this mass, which will be tentatively referred to as the Behrmann massif, and that of the Kubor and Bismarck massifs, is consistent with the notion that these blocks were positive during the Mesozoic. This possibility will also be examined in a later section.

The southeastward continuation of the cordilleran trough is obscured by the presumably Tertiary rocks which form the northern extension of the Aure trough in the Aure-Watut River region (David, 1950; Map 1). It is my opinion that the Mesozoic geosyncline extended into eastern Papua but was split by the metamorphic massif which formed the heart of the Owen Stanley Ranges. It is likely that some, but not all, of the Mesozoic geosynclinal sediments in this region have been metamorphosed (G.A.V. Stanley, NF, 1946).

1.8 PRE-JURASSIC DIASTROPHISM

Pre-Jurassic sedimentary rocks (Triassic and Permian) are found only in a few widely scattered and very restricted localities of western Papua and New Guinea. Consequently, the lithology of these units, which will be described in the following pages, provides only a vague idea of the local conditions of deposition and practically nothing about the regional diastrophic framework.

However, some older Paleozoic rocks (Silurian to Carboniferous) such as occur extensively in parts of West Irian (Visser and Hermes, 1962) may have been deposited in the central cordilleran region, but were subsequently folded, metamorphosed and intruded by acid to intermediate rocks during a Paleozoic (Hercynian ?) phase of orogenesis. These rocks are considered to be part of the crystalline basement complex (Section 1.8.3).

1.8.1 Triassic

Very recently D.B.Dow and F.E.Dekker (1963) have reported the presence of Triassic sedimentary rocks in the western Bismarck Range of the central cordillera. These are the first fossiliferous Triassic rocks to have been found anywhere in New Guinea. The rocks are Upper Triassic (Carnian-Norian) and have been subdivided into two units each greater than 600 meters in thickness. The upper unit consists of feldspathic arenite, red

tuffaceous shale, and conglomerate; all of which were derived from acid volcanics. The second, lower unit, is comprised of richly fossiliferous graywackes. S.K. Swarko (1963) has briefly discussed this fauna which includes the cephalopod: Sirenites sp. and the pelecypoda: Costatoria sp., Myophora sp.

Pre-Jurassic rocks 50 meters thick were penetrated in the Barikewa bore. These rocks consisted of calcareous sandstones and micaceous siltstones grading downward into terrestrial, commonly conglomeratic arkoses and red beds which are suspected to have been deposited on a basement of granitic composition. Here as in the western Bismarck Range there appears to be a considerable angular unconformity (ca. 35°) between these beds and the overlying Jurassic. It is interesting to note that the Komewu No. 1 bore bottomed in sub-Jurassic dacite that may be related in some way to the Triassic dacite conglomerate occurring in the western Bismarck Range.

It appears that, although Triassic rocks accumulated as far south as Barikewa and Komewu, the original distribution of these rocks was probably very patchy rather than a continuous blanket-like accumulation. The patchy distribution of the Triassic sediments is not likely to have been the result of post-depositional erosion because Triassic sedimentation was followed by the accumulation of the thick Jurassic and Cretaceous geosynclinal sequences. The angular unconformity found between the Triassic and Jurassic rocks is tentatively attributed to tilting of fault-defined blocks associated with the Jurassic and Cretaceous subsidence of the Papuan geosynclinal system.

1.8.2 Permian

The oldest known sedimentary rocks occurring in the Territory of Papua and New Guinea are Permian. These rocks occur in the vicinity of the Kubor Range in the central cordillera. The Permian age of the sediments was first determined by Glaessner (Glaessner, Llewellyn and Stanley, 1950) on the basis of foraminifera. The rocks were subsequently mapped and described by Rickwood (1955). These rocks (Kuta Group) rest unconformably for the most part on the Kubor granodiorite and in a few places rest on basalt and the Omung metamorphics, all of which form the crystalline core of the Kubor Range. The lower units consist of calcareous arkose which grades upward into pure limestone. Where the Permian rests upon the metamorphic basement the lower units consist of calcareous shale-breccias. Macrofossils, mostly brachipods, occurring in the limestone units include: Dielasma sp., Spiriferina sp., Rhynchonella sp., and others. Interestingly enough, Rickwood notes that this fauna does not appear to have close affinities with either the eastern Australian, western Australian or Timor Permian. The maximum thickness of the Kuta Group is estimated at about 250 meters.

In the Imbrum River area of the Bismarck Range, McMillan and Malone (1960) found an isolated mass, more than a kilometer long, of arenaceous limestone and conglomerate which rests unconformably on the Bismarck granodiorite. They very tentatively suggest that these rocks may be equivalent to the Kuta Group (Permian).

It is likely that the original extent of the Permian was very restricted and accumulated in very shallow discontinuous seas which spread over a crystalline

platform of low relief.

1.8.3 Crystalline Basement

Information concerning the nature of the crystalline rocks, that form the sub-Mesozoic basement complex, is derived from two main regions. Several bores in southwestern Papua have penetrated the basement and provide information concerning the composition, areal distribution and to some extent the age of the crystalline rocks forming the Fly-Digoel platform. Similar information is available in the heart of the central cordillera where the crystalline basement rocks are exposed by virtue of the very important vertical movements that have accompanied the development of the orogen.

Southwestern Papua.-- Crystalline basement rocks outcrop in the Mabaduan Hill (Plate 1) on the southern edge of the Oriomo Plateau. The basement rocks there vary from medium-grained biotite granite to coarse granodiorites intruded by pegmatites. Similar rocks were encountered in less than 600 meters in the Oriomo bores on the axis of the Oriomo Plateau. At Aramia the bore entered biotite-granite at about 2000 meters after passing through a zone of granitic boulders in a matrix of strongly weathered granitic sand. A potassium-argon age determination on a biotite concentrate from this granite indicated that it is Upper Permian and near the Triassic boundary.* However, since the rock is quite weathered, it is likely that this preliminary determination represents a minimum age for the granite and a maximum for

* Bureau of Min.Resources, Geology and Geophys., written communication to Island Exploration Co., 1962

the overlying sediments. Granitic rocks were also encountered in the Komewu No.2 bore at a depth of about 3000 meters. These differ somewhat from the granites to the south because they did not contain biotite, and feldspar was more abundant than quartz.

Central cordilleran region.-- The crystalline basement complex in the central cordillera consists of two principal units: (1) a metamorphic sequence which is intruded by (2) granodiorite batholiths. In the Kubor Range Rickwood (1955) found the basement complex to consist in part of a series of low-grade metamorphic, highly folded, argillaceous rocks. According to Rickwood the most common rock types are grayish-black slate and thinly-bedded calcareous greenish-gray slate. No fossils have been found in these rocks and they can only be dated as pre-Permian. These rocks, the Omung Metamorphics, have been intruded by a granodiorite mass (Kubor Granodiorite) which is also pre-Permian. It has been suggested that the intrusion of the Kubor granodiorite was early Tertiary. However, this notion is disproved by Rickwood's mapping which demonstrates that the Permian rests unconformably on both the granodiorite and metamorphics and was to a large extent derived from it. The Kubor mass is here considered as basement, at least as far as the Mesozoic and Tertiary development of the New Guinea orogen is concerned.

A generally similar basement complex has been mapped by McMillan and Malone (1960) in the Eastern Highlands district of New Guinea. Here a particularly large portion of the basement complex is composed of metamorphic rocks which McMillan and Malone have split into two formations. The younger of the two (Goroka Formation) consists of black schistose siltstone,

biotite-andalusite-schist, carbonaceous schist, quartzite, phyllite, quartz graywacke, calcarenite, calcareous siltstone and minor limestone. The older formation (Bena Bena Formation) consists of chlorite-actinolite-schist, arkose, phyllite, quartz muscovite schist, granite gneiss, porphyroblastic feldspathic siltstone and quartzite. McMillan and Malone consider these rocks to be Paleozoic and tentatively correlate the Goroka Formation with the Omung metamorphics in the Kubor Range.

As was the case in the Kubor Range, these basement metamorphic rocks are intruded by a large (48 x 18 km) granodiorite batholith (Bismarck Granodiorite). According to McMillan and Malone the batholith contains a wide variety of rock types, including granite, quartz-oligoclase rock, gabbro and ultrabasics as well as the more common granodiorite and quartz diorite. They consider the batholith to be the same age as the Kubor batholith; i.e., pre-Permian.

Dow and Dekker (1963) have the opinion that the Bismarck Granodiorite is post-Triassic and probably early Jurassic. This conclusion is based on the notion that the granodiorite is intrusive into presumably Triassic sediments along its southern margin. It is not certain, however, that these sediments are Triassic. In fact Rickwood (1955) thought that these same rocks were Paleozoic and part of the Omung Metamorphics. Furthermore, it is possible that the granodiorites observed in contact with the sedimentary rocks may be part of a series of late Tertiary stocks which are found along the length of the entire Bismarck Range. Indeed, such a stock is known to separate Mesozoic sediments from the western end of the main Bismarck batholith (Dow and Dekker, 1963). Until the

age of the Bismarck batholith is convincingly established I prefer to think that it, like the Kubor batholith, is pre-Permian and part of the crystalline basement.

Western cordilleran region.-- A very extensive system of metamorphic rocks forms the northern flank of the western cordillera extending from the Sobger River on the west to at least the April River on the east (Plate 1, Map 1). These rocks are also considered to be a portion of the pre-Mesozoic crystalline basement. However, very little is known about the geology of this region and there is some suggestion that the history of orogenesis and metamorphism has been quite different from that of the central cordilleran region.

The best description of these metamorphic rocks is that of Bär et al. who studied these rocks in the Boendermaker Range of the Star Mountains region. The rocks have been subjected to considerable dynamo-metamorphism producing a degree of metamorphism corresponding to that of the chlorite-zone. The whole sequence, which includes schist, quartzitic sandstones, and some marble, has been intensely folded and subsequently faulted. The age is unknown although in the upper Sepik they are pre-Tertiary. Such rocks are assumed to continue eastward into the Behrmann Range on the north watershed of the main cordillera. There is no indication as to how far east these rocks extend.

1.9 PRINCIPAL DIASTROPHIC PHASES

On the basis of the preceding studies it is proposed that the diastrophic evolution of western Papua and New Guinea; i.e., the development of the Papuan geosynclinal system and the growth of the New Guinea orogen, can be subdivided into four main phases as follows:

1. Initial taphrogenic phase characterized by the fragmentation of a cratonic platform and the development of the Mesozoic Papuan geosynclinal system.

2. Stabilization of the orthogeosynclinal system in the latest Mesozoic and Paleogene to form a quasi-platform.

3. Retrogressive taphrogenic phase marked by renewed fragmentation of the Paleogene quasi-platform giving rise to the Lower and Middle Miocene Papuan geosynclinal system.

4. Orogenic phase defined by the inversion of the geosynclinal system and the uplift of the main New Guinea cordillera as well as the formation of the Upper Miocene and Pliocene exogeosyncline.

Superficially these subdivisions are in part similar to the main phases in the consolidation or cratonization of the earth's crust as envisioned by H. Stille (1955). Indeed, consideration of Stille's concepts has led me to the recognition of the above main phases in the diastrophic evolution of western Papua. There are, however, considerable and fundamental differences between these

two schemes which will become evident in the next few pages.

1.9.1 Initial Taphrogenic Phase

The development of the New Guinea orogen had its inception in the early Mesozoic. This main stage in the diastrophic evolution of the orogen was preceded by a period of Paleozoic (Hercynian ?) orogenesis, plutonism and metamorphism that is thought to have culminated in the formation of a quasi-craton in the true sense of Stille. These early earth movements, which are recorded mainly in the Bismarck and Kubor crystalline massifs, are beyond the scope of this study.

The lithologic character of the Papuan Triassic and Permian sediments suggests that prior to the Permian the consolidated Paleozoic (?) geosynclinal terrain (quasi-craton) was reduced to a surface of low or moderate relief over which was spread the thin, discontinuous deposits of arkosic or "granite-wash" sediments such as the Kuta Group of the Kubor Range area and the pre-Jurassic rocks encountered in the Barikewa bore. Fragmentation of the Papuan quasi-craton began during the Mesozoic and is attributed to tensional stresses which will be discussed in Section 3.1. The fragmentation resulted in the formation of the cordilleran and the Kutubu intrageosynclinal troughs as well as the intervening Kubor and Bismarck massifs. Fragmentation of the platform was associated with considerable volcanism especially in the central cordilleran region as evidenced by the Jurassic basic marine volcanics and the early Cretaceous Kondaku tuffs.

The general nature and thickness of the sediments which developed in the two main intrageosynclinal troughs

and on the Fly-Digoel platform are summarized in Plate 2.

1.9.2 Stabilization Phase

The sedimentary character and distribution of the late Cretaceous rocks indicate a decline in the rate of geosynclinal sinking in western Papua (Kutubu trough). At that time the Fly-Digoel platform was beginning to extend northward at the expense of the Kutubu trough. The late Cretaceous sedimentary sequences developed in the Wahgi trough, although typically geosynclinal in the lower units, grade upward into sediments more typical of a relatively shallow water, platform environment. There was still some volcanism in the western Bismarck area. By the Paleogene, however, platform conditions were nearly universal and extended northward far beyond the present margin of the Fly-Digoel shelf, crossed the site of the Mesozoic Kutubu trough and incorporated at least part of the Kubor-Bismarck geanticlinal massifs. The Ramu trough may have survived stabilization. Figure 18 illustrates the progressive stages in the expansion of the Fly-Digoel platform due to the stabilization of the intra-geosynclinal troughs.

There is no evidence that the stabilization of the geosynclinal belts in western Papua and New Guinea was provoked by folding, magmatism and metamorphism as Stille advocates for the cratonization of orthogeosynclines. This fact constitutes the main difference between Stille's concept of cratonization of geosynclinal terrains and the modified view I have suggested for the stabilization of the Mesozoic Papuan geosynclinal system. As shall be pointed out in a subsequent section, it is more likely to have been caused by a temporary relaxation of the extensional stresses which are postulated to have given

GENERALIZED, COMPOSITE STRATIGRAPHIC SECTIONS

WESTERN PAPUA AND NEW GUINEA

FLY-DIGOEL PLATFORM

CENTRAL FOOTHILLS HINGE ZONE (KUTUBU TROUGH, ERAVE-WANA SWELL, PURARI BASIN)

CENTRAL CORDILLERAN GEOSYNCLINAL REALM (WAHGI, RAMU AND KAUGEL INTRAEOGYNCLINAL TROUGHS)

PLIOCENE
MIOCENE
EARLY CRETACEOUS
JURASSIC
PALEOZOIC



MUDSTONE, MARL, LIGNITE
ARGILLACEOUS LIMESTONE, MARL
LIMESTONE, MUDSTONE
MUDSTONE, SANDSTONE
MUDSTONE, ARKOSIC, CARBONACEOUS SANDSTONE
"GRANITE"

KM
0
5

SOLID LINES DEFINE PRINCIPAL DIASTROPHIC EPISODES
DASHED LINES TIME LINES

NON-MARINE SANDSTONE, MUDSTONE
MUDSTONE, SILTSTONE, COAL
SANDSTONE, MUDSTONE

MUDSTONE, SANDSTONE

MARL, ARGILLACEOUS LIMESTONE
ARGILLACEOUS LIMESTONE
CLASTIC LIMESTONE
GLAUCONITIC SANDSTONE

GRAYWACKE, MUDSTONE

MUDSTONE, SILTSTONE

ARKOSIC SANDSTONE, CONGLOMERATE

OROGENESIS

RETROGRESSIVE
TAPHROGENESIS

STABILIZATION

INITIAL
TAPHROGENESIS

PORPHYRITIC BASALTS, ANDESITE,
RHYOLITE, TUFF, AGGLOMERATE

GRAYWACKE

CONGLOMERATE, TUFF
GRAYWACKE

PORPHYRITIC LAVAS

LIMESTONE LENSES

BLACK SHALE, SILTSTONE

CONGLOMERATE, GRAYWACKE

CLASTIC LIMESTONE, SANDSTONE
CONGLOMERATE, AGGLOMERATE
PILLOW LAVAS

GRAYWACKE

SILTSTONE, SHALE

TUFFACEOUS SILTSTONE

BASALT, AGGLOMERATE
SHALE, SILTSTONE
LIMESTONE LENSES, GRAYWACKE

PILLOW LAVAS, AGGLOMERATE

GRAYWACKE

ARKOSE, DACITE CONGLOMERATE

GRAYWACKE, SILTSTONE

ARKOSE, LIMESTONE

GRANDIODORITE, SCHIST

PHYLLITE, QUARTZITE

QUATERNARY AND
PLIOCENE

MIDDLE MIOCENE

TAURIAN

KERERUAN

PALEOGENE

LATE

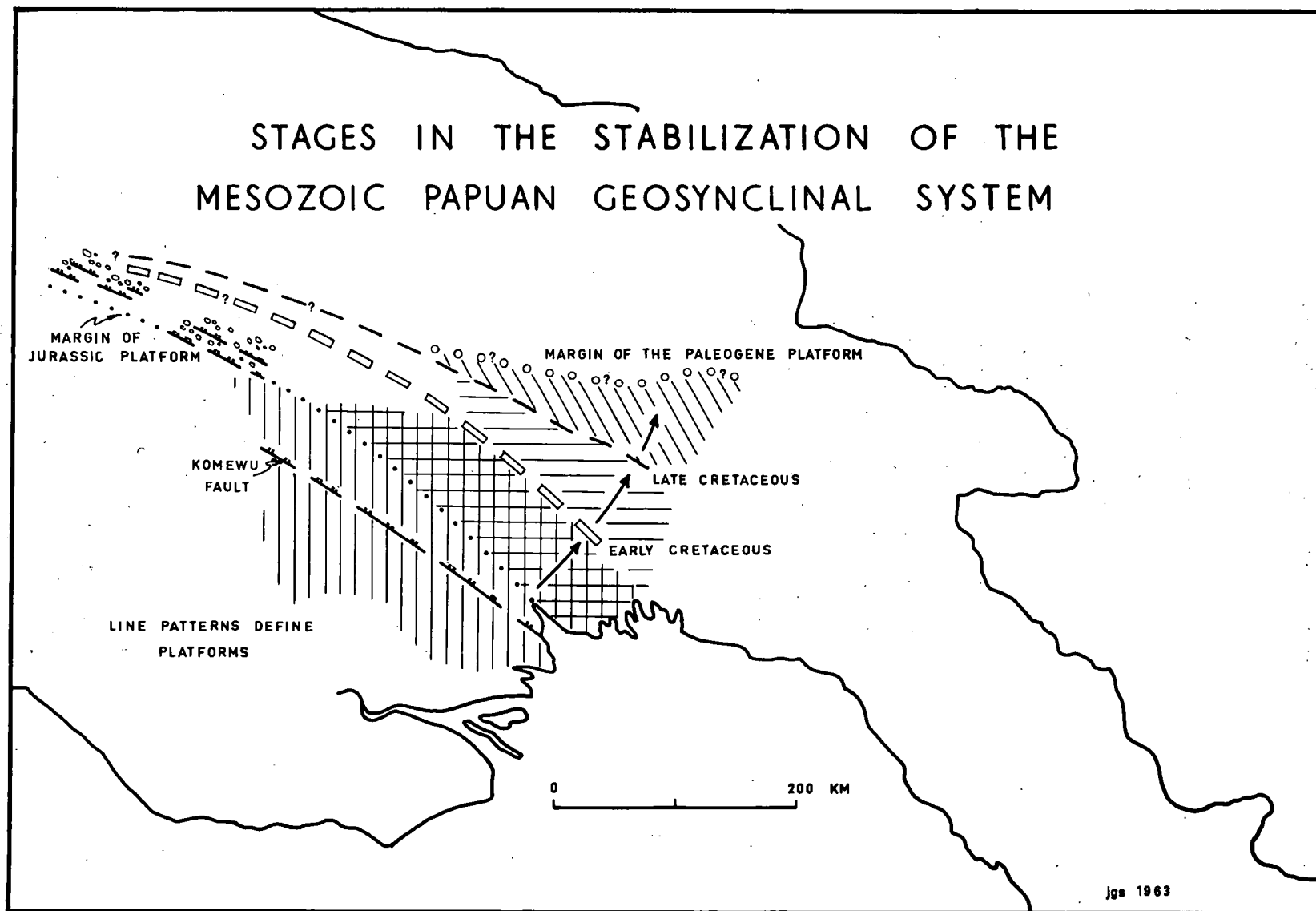
EARLY

JURASSIC

PERMO-TRIASSIC

PALEOZOIC

Figure 18



rise to the development of the Papuan geosynclinal system.

1.9.3 Retrogressive Taphrogenic Phase

The advent of the late Lower Miocene was marked by a rather violent renewed phase of geosynclinal fragmentation and sinking. The formation of the Omati and Kaugel troughs and the intervening Erave-Wana geanticlinal swell in the central foothills region is attributed to the regeneration of taphrogenic processes. These features were superimposed on the terrain underlain by the Kutubu trough. The cordilleran trough and the Kubor and Bismarck massifs were also resurrected. A very intense phase of volcanism was associated with the Lower Miocene development of the Bismarck massif as indicated by the thick Daulo Volcanics.

1.9.4 Orogenic Phase

In western Papua and New Guinea the Middle Miocene represents a transition from the taphrogenic to the orogenic phases of diastrophism. In fact the embryonic stage in the development of the central cordillera may have been initiated to some extent in the Lower Miocene. In any event the Middle Miocene sedimentary patterns suggest that the Kubor and Bismarck geanticlinal massifs had consolidated and were advancing southward at the expense of the Kaugel trough which was, nevertheless, still the site of thick geosynclinal accumulation. The southern edge of the trough was active as indicated by the extensive development of conglomerates and sedimentary slump structures along the northern margin of the Erave-Wana swell in the Pio River region. At this stage the swell had broadened and included the region of the moribund Omati trough. In a sense the Erave-Wana swell

lost much of its original geanticlinal character and at this stage is probably best thought of as a more or less mobile edge of the Fly-Digoel platform.

Orogenesis began in earnest during the Upper Miocene with the rapid morphogenic uplift of the central cordilleran region. By this time the Kaugel trough was defunct and its northern margin was already uplifted and subject to erosion. In its place an exogeosynclinal trough developed around the southern margin of the growing orogenic tumor. The main Erave-Wana swell had by this time ceased to exist but was replaced by a subordinate feature, the Darai swell. The platform-type limestones developed in the western cordilleran region suggest that intensive orogenic uplift had not yet begun in that region during the Upper Miocene.

In the Pliocene uplift continued according to the same general pattern as was roughed out in the Upper Miocene but with greater intensity. Uplift of the central cordillera was accompanied by considerable volcanism as well as denudation and erosion. The resulting sediments were deposited in the adjacent exogeosynclinal troughs at a rate often exceeding subsidence, hence, giving rise to the very thick marine and non-marine clastic wedge in the Delta embayment region. By this time vigorous uplift associated with extensive volcanism was proceeding in the western cordilleran region and a considerable clastic wedge was accumulating in the exogeosynclinal trough to the south, the Digoel-Strickland basin.

The development of the fundamental structural framework of the cordillera (i.e., primary tectogenesis) was

cognate both in terms of time and space with the morphogenic uplift of the cordillera. However, the foreland folded belt of the central foothills region was the result of secondary tectogenic processes which were restricted to a single episode, probably Plio-Pleistocene, in the orogenic evolution of the New Guinea cordillera.

1.10 MAGMATISM

Nearly every principal phase in the diastrophic development of western Papua and New Guinea was accompanied by important volcanism. In this respect the magmatic development of New Guinea conforms to the patterns manifest in other circum-Pacific orogens. Ultrabasic magmatism has also been quite important; while on the other hand, intermediate to acid plutonism has played a relatively small role in the magmatic history of the orogen.

The subsequent pages are devoted to a brief descriptive review of the nature and distribution of magmatic rocks throughout Papua and New Guinea. Particular attention is directed to the temporal relationship of these rocks and the main diastrophic phases in the evolution of the New Guinea orogen.

1.10.1 Volcanism

As is typical of circum-Pacific orogenic systems, volcanism has played a major and continuous role in the magmatic development of New Guinea. However, because the vast volcanic sequences found throughout the orogen have never been studied in great detail, the following discussion is limited to a general consideration of the evolution of volcanism in New Guinea. Information concerning the composition and distribution of volcanics, that have been mentioned in previous sections, is

summarized in Plate 3.

It is easily seen on this figure that volcanism was active throughout almost the entire history of the geosynclinal system since its inception during the Permo-Triassic. This nearly continuous volcanic sequence can be subdivided, superficially at least, into two main sub-groups which correspond to the taphrogenic and orogenic phases of diastrophism. The first group is represented by the Mesozoic volcanics of the central cordillera region. They consist predominantly of basaltic lavas and agglomerates of which some have had a marine origin as evidenced by the presence of pillow lavas and their association with Mesozoic marine sediments. These volcanics are apparently intimately linked with the main phases of the initial fragmentation and sinking of the Papuan geosynclinal system.

The second group is the Upper Miocene (?) to Recent volcanics which seem to be dominantly andesitic in composition with subordinate basalts. These are associated with the orogenic or mountain-building phase of diastrophism. The relationship shown here between the andesitic (Pacific) volcanism and the orogenic phase of diastrophism on one hand, and geosynclinal or initial basaltic volcanism and the taphrogenic phase on the other hand, is in general typical of a normal diastrophic cycle (Rittmann, 1962, p. 163). This is especially true in the development of Pacific orogens.

It is equally interesting and significant to note that there was at least one, perhaps two, breaks in the volcanic history which correspond to particularly crucial stages in the overall development of the orogen. The

MAGMATISM AND DIASTROPHISM					
	DIASTROPHISM	VOLCANISM	PLUTONISM		
QUATERNARY		andesitic and basaltic composite volcanoes Central Cordillera rhyolite flows Central Cordillera andesitic flow tuff, agglomerate Central Cordillera	granodiorite Western Cordillera diorite Central Cordillera quartz-dolerite Central Cordillera gabbro		
Pliocene	Orogenesis	andesitic tuff agglomerate Central Cordillera spherulitic rhyolite			
MURUAN					
IVORIAN					
TAURIAN	Retrogressive Taphrogenesis	hornblende-pyroxene porphyry, tuff Central Cordillera	Marum ultrabasic belt serpentinite, dunite Central Cordillera gabbro		
KERERUAN					
PALEOGENE	Stabilization				
LATE		basic marine volcanics pillow lavas, tuff Central Cordillera (Western Bismarck Range) basaltic agglomerate			
EARLY		andesitic tuff Central Cordillera basaltic lavas	Marum ultrabasic belt Central Cordillera		
JURASSIC	Initial Taphrogenesis	basic marine volcanics basaltic lavas, agglomerate pillow lavas Central Cordillera (?)basalt, volcanic breccia Western Cordillera acidic eruptions indicated by dacite conglomerate and Central Cordillera highly feldspathic sediments Komewu No.1 bore Central Cordillera (Kubor Range)	?? Bismarck granodiorite		
PERMO-TRIASSIC					
PALEOZOIC			Kubor and Bismarck granodiorite Central Cordillera		

JGS 1963

first such break occurred during the Paleogene and may have extended into the early Lower Miocene (Kerueruan). As yet there have been no volcanics of this age found anywhere in western Papua and New Guinea. This period of apparent volcanic quiescence corresponds with the Paleogene stabilization of the Mesozoic Papuan geosynclinal system. As I have previously described (Section 1.9.2, Fig.18) this stabilization began in the south during the late Cretaceous and moved northward, finally culminating in the creation of a quasi-platform characterized by calcarenitic and sandy platform deposits. The quasi-platform probably extended as far north as the present western Bismarck Range which had been the site of important Mesozoic volcanism. I have already suggested, and will develop shortly, that this temporary stabilization may have been due to a relaxation of the tensional stresses which produced geosynclinal fragmentation, and sinking. This mechanism could easily account for the cessation of volcanism, because a regional tensional stress environment is likely to provide the optimum conditions for volcanism (Rittmann, 1962). Tensional stresses can produce deep fractures which in many cases would be capable of penetrating even the upper mantle. Furthermore, the hydrostatic pressure would be reduced in the rifting zone (i.e., the geosyncline). Both these factors would promote the migration of basic and ultrabasic magmas into the upper layers of the crust.

Volcanism resumed during the late Lower Miocene (Taurian) with the retrogressive stage of geosynclinal development. There may have been a second, temporary lull in volcanism during the Middle Miocene which corresponded to the transitional phases of taphrogenesis and orogenesis.

1.10.2 Ultrabasic Plutonism

Although ultrabasic rocks were reported by E.R. Stanley in 1919, only very recent field work has shown that a very large ultrabasic belt is associated with the major orogenic structures of the New Guinea cordillera (Fig.19). The ultrabasic belt is a nearly continuous series of pod-shaped masses (each about 50 by 130 kilometers) extending from the head of the Huon Gulf southeastward along the northeastern flank of the Owen Stanley Range for nearly 400 kilometers. In general the belt is a typical alpine ultrabasic suite consisting of peridotites, pyroxenites and dunites most of which have been serpentized to some extent (Dow and Davies, 1961; Smith and Green, 1961 and Davies, 1959). These rocks are also associated in some instances with calc-alkaline rocks from gabbroic and intermediate to acidic types.

As yet there is very little information which sheds light on the mechanism and time of emplacement. The belt is associated with important fault zones especially on the west and southwest, the Owen Stanley fault. This relation suggests a tectonic emplacement. However, there appears to be a rough zoning from ultrabasics through basic and intermediate to acidic rock types which probably resulted in part from gravitational differentiation. In consideration of these two relations it is possible that these rocks are of a pseudo-stratiform type similar to those in New Foundland, Cuba and the Philippines (Green, 1961) and hence may have been emplaced to some extent by both magmatic and tectonic processes. It is impossible at present to resolve the age of emplacement closer than Cretaceous to Lower Miocene.

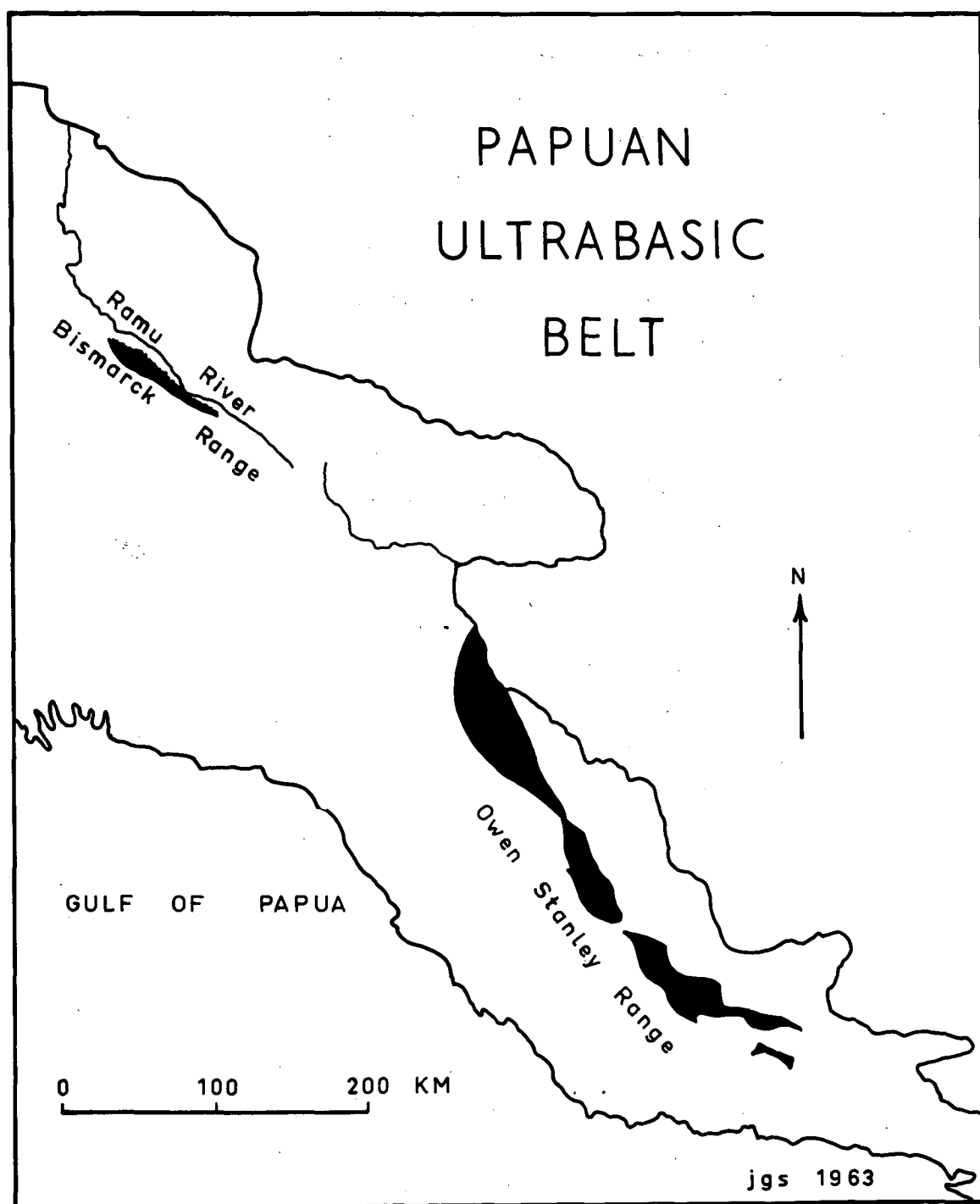


Figure 19

The second, much less extensive suite of ultrabasic intrusives occurs on the southwest side of the Owen Stanley Range in the Port Moresby district. There Glaessner (1952) describes small lenticular and discontinuous outcrops of serpentine which are associated with a major fault system that cuts through the region. They are tentatively dated as post-Eocene to pre-Middle Oligocene.

Both the above ultrabasic occurrences will be analyzed in detail by R.P.B. Pitt who is making a tectonic study of central and eastern Papua.

Similar occurrences of ultrabasic rocks have recently been reported in the central cordillera region that are very likely to be related to those in the Owen Stanley Ranges (Plate 1). Dow and Dekker (1963) have described a very large ultrabasic mass (Marum basic belt) on the northeast flank of the western Bismarck Range. The belt is at least 110 kilometers in length and has a maximum width of 15 to 25 kilometers. The belt consists of gabbro, dunite, serpentinite and some pyroxenite.

The age and mode of emplacement is unknown. Dow and Dekker suggest that these rocks were probably emplaced during the lower Tertiary. As was the case with the main Owen Stanley system; the Marum basic belt is associated with important faulting on the southwest. It is bounded on the northeast by the Ramu River valley which has long been recognized as an important tectonic lineament and is very likely to be a zone of considerable vertical and transcurrent faulting. The Owen Stanley ultrabasics also fall along the extension of this line.

McMillan and Malone (1961) have also reported two relatively small isolated masses of serpentinite in the Kami area (lat $6^{\circ}15'S.$; long $145^{\circ}25'E.$) on the southwest side of the Bismarck Range. These serpentinites were intruded into Cretaceous and Eocene rocks. McMillan and Malone suggest that they are related to the stage of late Tertiary faulting and folding.

On the basis of general patterns of diastrophism which have emerged in the preceding sections, it is possible to make several prognoses as to the time and mechanism of ultrabasic magmatism in western Papua and New Guinea. It seems most reasonable that the diastrophic environment was most suitable for ultrabasic magmatism during the main phases of Cretaceous taphrogenesis or perhaps the late Lower Miocene (Taurian) phase of retrogressive taphrogenesis. At these times tensional stresses related to taphrogenesis were at a maximum, a condition which would provide easy access for the ultrabasic fluids or crystal slurries into the geosynclinal troughs as the so-called ophiolitic intrusions. This magmatism might be manifested at the surface by basic and intermediate volcanism.

Again on environmental grounds I would think the Paleogene to be an unlikely time for the emplacement of ultrabasic materials because the Paleogene sedimentary patterns indicate that nearly the entire Papuan geosynclinal system was subjected to temporary stabilization at that time. Indeed, even the Miocene "e" to Upper Cretaceous Asai beds of the western Bismarck Range include quartz sandstones, calcarenite and conglomerates, which suggest that stable platform conditions may have extended into that region during the Paleogene. Furthermore, the

striking absence of volcanics is further interpreted to mean that tectonic conditions in the central cordillera were far from optimum for magmatic processes of any type. Of course, it is possible, but unlikely, that external volcanism had given way to internal ultrabasic intrusion.

On these grounds I would prefer to think that the ultrabasic belts of the central cordillera are mainly Mesozoic and first gained access to the upper crust and into the geosynclinal troughs by purely magmatic processes enhanced by a regional tensional stress environment. The ultrabasic materials could have entered the crust as a fluid as advocated by Hess (1955), as a crystal mush (Bowen and Tuttle, 1949) or perhaps they developed in part from submarine picritic lavas as proposed by Bailey and McCallien (1953). However, in subsequent orogenic phases of diastrophism these rocks were probably raised to much higher levels in the crust by purely tectonic mechanisms as indicated by their intimate association with major fault zones. According to Carey (1962) it is also conceivable that the ultrabasic belts are slices of the sub-geosynclinal simatic crust or mantle which have been tectonically injected into the axial zone of the orogen.

1.10.3 Basic to Acid Plutonism

There has been very little basic to acidic plutonism associated with Mesozoic and Tertiary diastrophism in Papua and New Guinea. Tertiary rocks of this type are restricted to a few relatively small plutons scattered along the orogenic zone.

The bulk of Tertiary plutonic rocks occur in the Eastern Highlands District of the central cordillera. There they are represented by a series of granodiorite and

gabbroic sills, dikes and small stocks which McMillan and Malone (1960) refer to as the "late Tertiary" intrusives. Along the southwestern margin of the Bismarck Range the rocks intrude "e" and "f₁₋₂" sediments. The largest body intruding Tertiary sediments is the Dunantina stock (10 by 5 kilometers) which is composed of hornblende gabbro. On the north side of the Bismarck Range in the Ramu Valley occurrences of plutonic rocks are limited to small dikes and sills of porphyritic andesite, microdiorite, microgranodiorite and rhyodacite. The stocks and sills of hornblende porphyry at Mount Michael (lat 6°25'S.; 145°20'E.) are probably also part of the late Tertiary phase of plutonism.

A group of larger bodies have intruded the Paleozoic metamorphic rocks of the eastern Bismarck Range in the Kainantu region (lat 6°15'S.; long 145°55'E.), but they have not been found to cut Tertiary rocks and their age is unknown. They are, however, probably part of the magmatic series discussed above; i.e., late Tertiary intrusives. The largest of these is the Yonkie stock which is a composite intrusion consisting of hornblende gabbro and in places monzonite and granodiorite. A large intrusive near the southern end of the Bismarck Range consists of hornblende diorite. There is some suggestion that this stock is overlain unconformably by "e" stage sediments, but the contact has not actually been observed. Other rocks associated with this group are composed of granodiorite and some olivine gabbro.

In the Western Highlands District Rickwood (1955) has described a series of quartz dolerite intrusives (Ga Intrusives) which are intimately associated with the major

faults paralleling the southwestern margin of the Bismarck Range. Rickwood has assigned these intrusives to the Pliocene.

Dow and Dekker (1963) have also reported a series of gabbro and granodiorite intrusives in the western Bismarck Range which they believe are probably Miocene (Oipo Intrusives).

Bar et al. (1961) have described a granodiorite batholith in the Antares area of the Star Mountains (Antares batholith). In addition to granodiorite this pluton and associated minor intrusives consist of augite-quartz diorite, hornblende diorite and hornblende gabbro. These rocks not only intrude sediments belonging to the Jurassic Bon Formation, but also have intruded and strongly metamorphosed limestones believed to belong to the New Guinea Limestone Formation (Lower Miocene). Hence, it is possible that these intrusives are late Tertiary in age and correspond to the similar phase of late Tertiary plutonism found in the central cordilleran region. The emplacement of the Antares batholith is thought to have been controlled to some extent by the major fault zones which cut the Star Mountains region.

All of the late Tertiary intrusives are thought to be most intimately related to the orogenic phases of diastrophism in western Papua and New Guinea.

2 TECTOGENIC DEVELOPMENT OF WESTERN PAPUA AND NEW GUINEA

The following discussion is devoted to the description and mechanical analysis of the folding and faulting which developed in the Papuan geosynclinal region primarily during the orogenic phase of the Mesozoic to Recent diastrophic cycle. In Papua and New Guinea, as is true of all the large orogenic belts throughout the world, the orogenic crustal movements have been expressed in a wide variety of tectogenic forms. There are two aspects to this diversity of folded and faulted structures: (1) morphologic differences and (2) contrasts in genesis and historical development. In the ensuing pages I will describe the morphology and historical development of the folded and faulted regions of western Papua and New Guinea and demonstrate that on these bases; i.e., morphology and historical development, the orogenic structures can be subdivided into quite distinct zones. I will also examine the structural characteristics of these regions in order to make inductions as to what tectonic mechanism(s) have been most active in this deformation. As a final, but important, step in this analysis I have sought for a common denominator in the mechanism of folding in order to determine whether or not these diversities of form and history may be the manifestations of a single diastrophic process. Such a common denominator does exist; namely, all the folded structures of the New Guinea orogen are intimately related to

differential vertical movements of the earth's crust.

Here I emphasize vertical movements as a strictly orogenic mechanism, since in the long run, horizontal movements are the truly fundamental type of movement that accounts for crustal deformation in both the taphrogenic and orogenic phases in the diastrophic evolution of a mountain system. This point will be clarified in Section 4.6.

2.1 NEW GUINEA MEGANTICLINORIUM

On the whole the structure of the central part of the New Guinea orogen is a broadly arched anticlinorium or meganticlinorium in the sense of Belousov (1962). This overall morphology is readily apparent on Figure 27 and Plate 4 which are sections drawn across the New Guinea cordillera. In this study we are dealing with the crestal region and the southwestern limb of this great structure. The crestal zone of the meganticlinorium includes the Kubor and Bismarck Ranges of the central cordillera and extends westward to the Star Mountains of the western cordilleran region. The oldest rocks in western Papua and New Guinea; i.e., the pre-Permian crystalline basement complex, outcrop in the core of this structure in the Kubor and Bismarck Ranges and progressively younger rocks are exposed to the southwest ranging from Permian to Recent.

The form and size of the meganticlinorium is best described by consideration of the surface developed between the crystalline basement and the overlying sediments. In the central cordillera the crystalline basement outcrops at altitudes often in excess of 3000 meters. To the southwest in the adjacent trough the basement rocks probably occur at depths of five to six thousand meters below sea level making the total relief of the basement surface at least 8000 meters. In the same context this trough can be considered a megasynclinorium which includes the southern part of the central foothills

regions and the Fly-Digoel plains. This synclinorium is quite asymmetric to the north and the very gently north-sloping Fly-Digoel platform forms the southern limb. The New Guinea meganticlinorium reflects the most fundamental process in the development of the orogen; namely, the differential vertical movements associated with the late Tertiary and Quaternary inversion of the Papuan geosynclinal system.

Within the realm of the New Guinea meganticlinorium two main types of folding can be recognized on the basis of morphology, origin and history of development. These have already been mentioned in Section 1.2.3 but will be repeated and elaborated upon at this point.

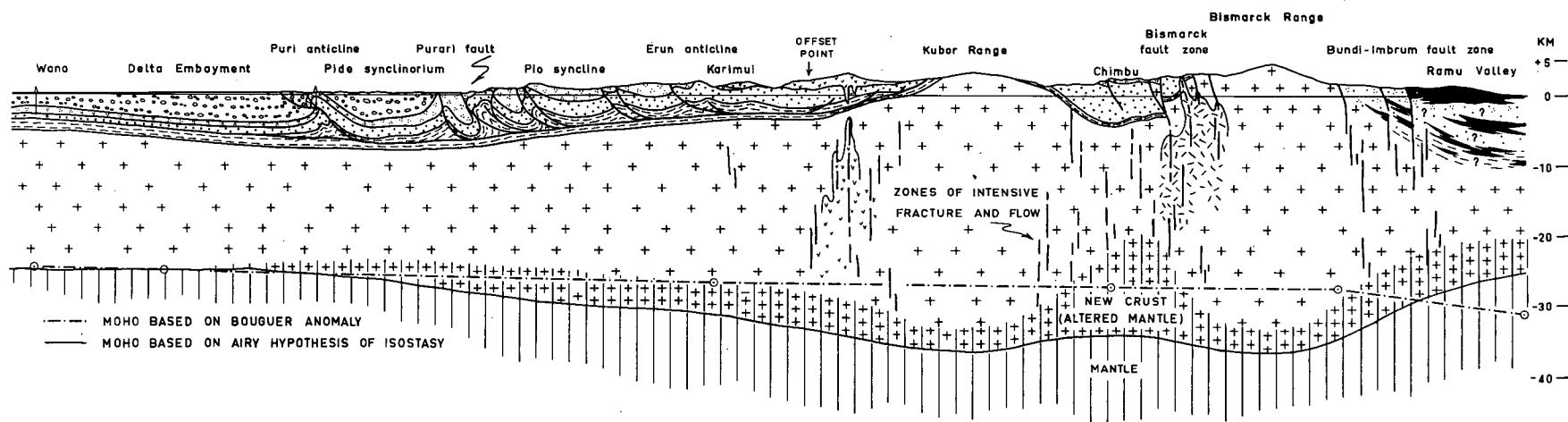
In the first group are the large, horst-like anticlinoria which form the core of the orogen in the western and central cordilleran regions and are, thus, intimately linked with the external morphology of the main cordillera. These folds are the direct result of the vertical movements associated with the inversion of the geosynclinal belt and, hence, are called primary folds. The processes of primary tectogenesis are of a secular nature and were active throughout the entire orogenic phase of diastrophism. To a certain extent these movements were inherited from the earlier geosynclinal phases of diastrophism.

The second group includes the continuous belts of smaller folds and faults which form a foreland folded zone in the central foothills region of western Papua. The foreland folded structures are of a more superficial and episodic nature and owe their existence to the inversion and lateral spreading of the geosynclinal zone during a

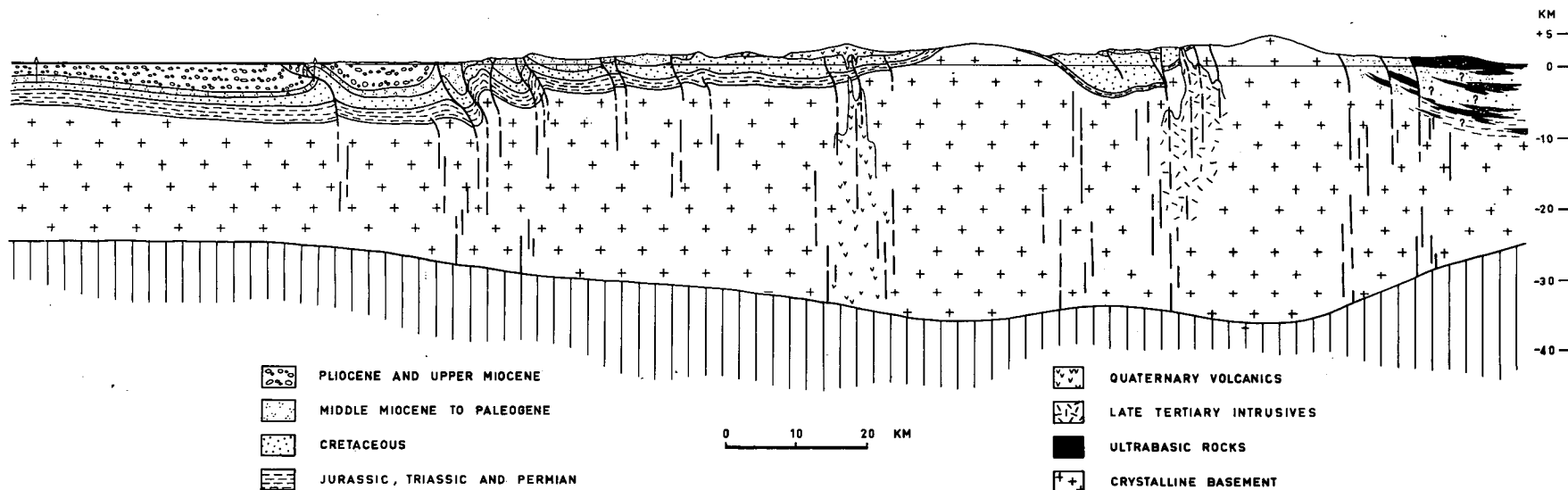
AND THE

PAPUAN FORELAND FOLD BELT

A. INTERPRETATION OF FORELAND FOLDS BASED ON DÉCOLLEMENT PRINCIPLE



B. INTERPRETATION OF FORELAND FOLDS ASSUMING VERTICAL MOVEMENTS OF FAULT-DEFINED BASEMENT BLOCKS



SURFACE DATA FROM AUSTRALASIAN PETROLEUM CO., 1961; McMILLAN AND MALONE, 1960; AND RICKWOOD, 1965

JOS 1003

very limited time span during the Plio-Pleistocene when orogenic movements were at the height of their development. In this respect they are a secondary effect of primary vertical movements and, hence, are referred to as secondary folds. The configuration of the secondary folds is also related to the geosynclinal framework of western Papua, but in a more passive sense than the primary folds.

The structural pattern of both these types of folding indicates that transcurrent movements of the crust have played an important role in the tectogenic development of the orogen.

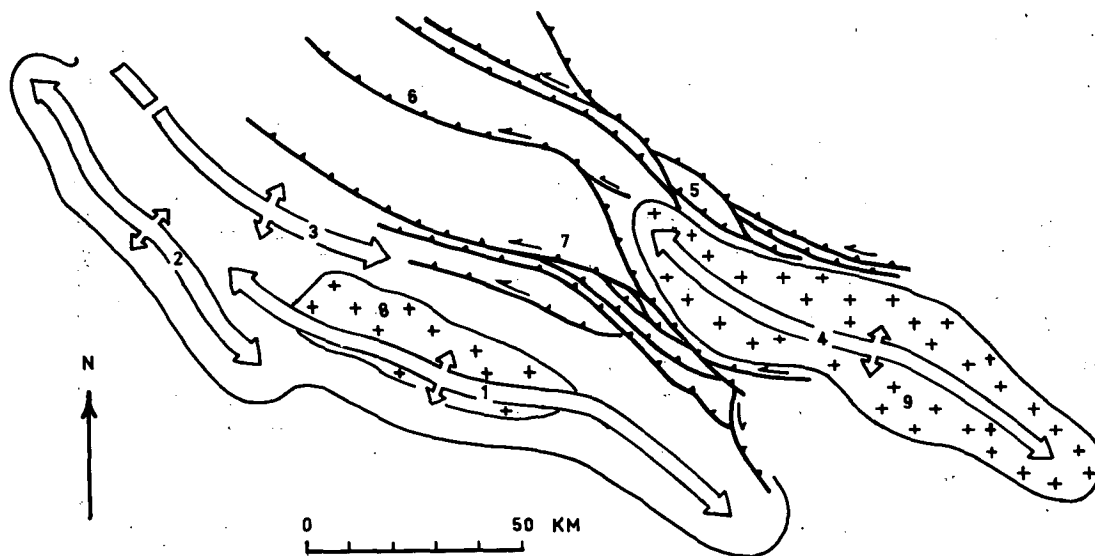
2.2 CENTRAL CORDILLERAN ANTICLINORIA

2.2.1 Structure

The central cordilleran region of the New Guinea meganticlinorium is formed by an en échelon system of four main anticlinoria: Kubor, Bismarck, Lai and Gumanche anticlinoria. The configuration of these large structures is shown in Figure 20 and Plate 4. The Kubor and Bismarck structures are the largest of this group and have played an important role in the diastrophic evolution of the region. Both of these anticlinoria are somewhat asymmetrical with the steeper flank to the southwest. In the case of the Bismarck structure this asymmetry is especially marked and associated with important faulting. In each of these two anticlinoria the crystalline core is one of its most outstanding features. This consists of Paleozoic metamorphics and granodiorite, which were discussed in Section 1.8.3. (Kubor and Bismarck Granodiorites; Omung, Goroka and Bena Bena Metamorphics). The crystalline complex forming the core of the Kubor anticlinorium consists mainly of granodiorite and is mantled by Permian and Mesozoic sedimentary rocks. The crystalline core of the Bismarck anticlinorium is larger and mantled by Lower Tertiary rocks.

Another structurally significant feature of the anticlinoria of the central cordillera is the pronounced sigmoidal plan which is clearly outlined on Figure 20. Along the crest of the Kubor Range east-southeast of

TECTONIC PATTERN OF THE CENTRAL CORDILLERA



MAJOR ANTICLINORIA



- (1) KUBOR
- (2) LAI
- (3) GUMANCHE
- (4) BISMARCK

MAJOR FAULT ZONES



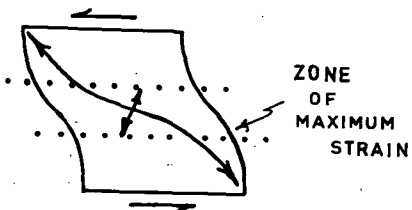
DOMINANTLY STEEP THRUSTS,
INFERRED LATERAL MOVEMENT AS
INDICATED

- (5) BUNDI
- (6) JIMMI
- (7) BISMARCK

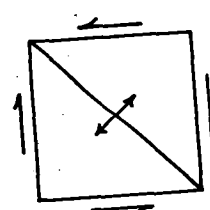
CRYSTALLINE MASSIFS

- (8) KUBOR MASSIF
- (9) BISMARCK MASSIF

STRAIN PATTERN



INFERRED STRESS PATTERN



ZONE
OF
MAXIMUM
STRAIN

Figure 20

Mount Hagen the Kubor anticlinorium has a west-northwest trend for about 80 kilometers. South of Chimbu, where the granite core of the anticlinorium finally plunges beneath the Mesozoic cover, the trend of the anticlinal crestal trace changes to nearly northwest-southeast and continues for at least another 90 kilometers. The western end of the Kubor anticlinorium plunges beneath the volcanic mantle of Mount Hagen and does not appear again on the other side. However, it is paralleled by the Lai and Gumanche anticlinoria which do continue beyond the Hagen Range in a northwesterly trend. As can be seen on Figure 20 the Bismarck anticlinorium, which lies to the east and en échelon with the Kubor anticlinorium, also has a pronounced sigmoidal plan.

Several zones of important faulting are associated with the anticlinorial development of the central massif. The most important of these fault zones is the Bismarck fault zone of Rickwood (1955) or the Gorgme thrust zone of Noakes (HA, 1939). This fault system parallels the southwestern margin of the Bismarck Range along a west-northwesterly trend. In this area it places presumably Paleozoic granodiorites of the basement complex in juxtaposition with Mesozoic sedimentary rocks and has been interpreted by both Rickwood and Noakes as being a high angle thrust. At both ends of the fault zone the strike of the faults changes to nearly northwest-southeast mimicking the sigmoidal pattern of the associated anticlinoria. These changes in trend are accompanied by a considerable splaying of the fault zone, which results in the formation of a "horse-tail" belt of imbricate thrust faults 10 to 15 kilometers wide north of Chimbu.

Recent mapping by Dow and Dekker (1963) for the

Bureau of Mineral Resources has shown that all of these fault zones are continuous into the western Bismarck Range. It is also significant to note that the faults have apparently served as avenues of intrusion for the late Tertiary plutonic rocks as indicated by the location of the G_a Intrusives (Section 1.10.3).

The northwest-trending Asaro-Watabung faults, that McMillan and Malone (1960) have mapped in the Eastern Highlands District, are probably the extension of the Bismarck fault zone. McMillan and Malone have described another fault system, the Bundi-Imbrum fault zone. The Bundi-Imbrum zone bounds the northeastern edge of the Bismarck Range and has also been interpreted as a system of thrust faults. The Marum ultrabasic belt is associated with this fault zone (Fig.20).

2.2.2 Origin of the Central Cordillera Anticlinoria

Vertical movements.-- Perhaps the major problem associated with the orogenic development of the central cordilleran region is the role of the crystalline basement in the processes of tectogenesis; i.e., folding and faulting. Rickwood has envisaged that an extensive surface was developed across the metamorphic and plutonic terrain in the cordilleran region which was eventually covered with Permian through Upper Miocene sediments. He then suggested that due to compressive stresses this surface, along with the overlying sediments, was folded during the late Tertiary phase of orogenesis. In defense of this argument he appeals to Lees (1952) who strongly advocated the notion that the basement rocks play an active role in the folding of the overlying sediments. I agree that the mapping done by Rickwood does in fact show that the

crystalline basement is intimately involved in the folding which affects the overlying sedimentary rocks. However, it is my opinion that these anticlinorial folds were in the process of development since the early Tertiary or even Mesozoic and not solely the result of a Pliocene compressive phase of orogenesis.

As was briefly pointed out in a previous section, it is likely that the Bismarck and Kubor crystalline massifs are fragments of the original Papuan anorogenic platform. During the Mesozoic and Tertiary phases of taphrogenesis these blocks were separated from the adjacent platform by the development of the Kaugel and Wahgi troughs. The incipient form of these anticlinoria was roughed out at that time by vertical faulting movements associated with taphrogenesis. In short these anticlinoria were positive areas, although not necessarily emergent, throughout the geosynclinal evolution of the central cordilleran region and owe a large portion of their form to relative subsidence of the intervening troughs and the draping of sediments over the crystalline blocks. The evidence for such activity in the central cordillera was developed in the preceding chapters which dealt with the framework of the region and can be summarized as follows:

- (1) The nature and thickness distribution of Jurassic rocks indicate that the Kubor region was already positive by that time. Volcanic materials found in the Jurassic deposits in the western Bismarck Range suggests emergence along the Bismarck trend.
- (2) Nature of the volcanic materials in the Cretaceous rocks again suggests some emergence in the central cordilleran region. The composition of the Cretaceous Purari graywackes suggests a granitic source, most likely the Kubor

massif.

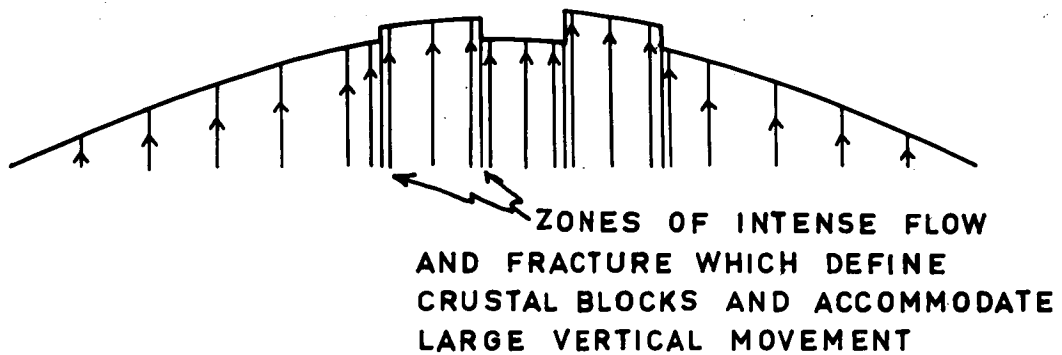
(3) Emergence of the Bismarck massif during the Lower Miocene is indicated by the conglomerate sequence fringing its southern margin.

Uplift of the central cordillera massifs assumed a more regional aspect during and after the Middle Miocene when a considerable area was emergent and contributing sediments to the marginal exogeosynclinal troughs (Upper Miocene and Pliocene). Nevertheless, vertical movements for reasons which will be discussed in Section 4 were still most pronounced around the Kubor and Bismarck anticlinoria. The early stages in the evolution of the central cordilleran anticlinoria can be visualized by reference to Plates 6 and 8.

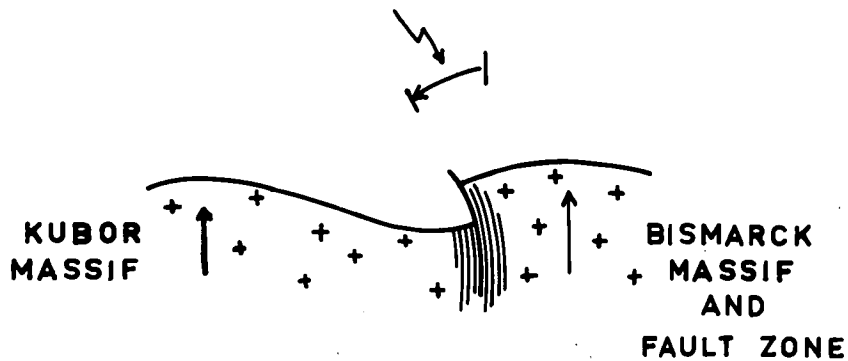
The structural pattern of the central cordillera can be explained in terms of a series of elongate crustal blocks moving vertically at varying rates (Fig. 21). The motion was primarily accomplished by flow which would normally be distributed fairly uniformly over a very wide area in this case corresponding to the entire New Guinea meganticlinorium. The blocks, however are defined by zones of abnormally rapid deformation. Depending on certain physical conditions; e.g. overburden, temperature, and the rate of strain, the deformation between the blocks can be by fracture rather than flow. This is particularly true in the higher levels of the crust where the temperature and hydrostatic stresses are low and consequently, the tensile strength and shear strength of the rocks are also relatively low. The Bismarck fault zone is the surface expression of one such a fracture separating the Bismarck massif from the adjacent Wahgi trough.

SCHEMATIC PATTERN OF VERTICAL MOVEMENT IN THE CENTRAL CORDILLERA

NEW GUINEA MEGANTICLINORIUM



GRAVITY SPREADING AT TOP
OF RISING BLOCK



Jgs 1963

Figure 21

Although these fractures are likely to be nearly vertical at depth, the upper part expands laterally and assumes a fan-like shape as the block moves above an adjacent block and in effect becomes an "over-thrust". Such a process is likely to have given rise to the steep, thrust-like character of the Bismarck fault zone. The fundamental processes producing the fragmentation of the crust into blocks and the subsequent vertical oscillations of these blocks will be discussed in more detail in the following sections.

Horizontal movements.-- The structural pattern of the central cordillera can not be completely and simply explained in terms of differential vertical movements between blocks. There is also quite striking evidence that horizontal (i.e., transcurrent) movements played a very important role in the development of the central cordilleran anticlinoria. Both the outstanding sigmoidal plan of the Bismarck and Kubor anticlinoria and their en échelon arrangement indicate the presence of a considerable transcurrent element in the overall deformation of the central cordillera. These complex en échelon and sigmoidal strain patterns imply internal rotation in simple shear about a vertical intermediate stress axis (or null axis) and are interpreted to be the superficial expression of movement along a deep-seated zone of shearing situated beneath the orogen. The nature of the simple shear deformation is shown schematically in Figure 20.

Figure 20 also illustrates the pattern of such deformation in the central cordillera anticlinorium. Barring the possibility that these sigmoidal and en échelon patterns may have resulted from over-printing of two intersecting fold trends as described by O'Driscoll

(1962); the geometry of the strain pattern permits one to infer the trend and sense of movement along the fundamental zone of shearing at depth. The Kubor and Bismarck sigmoidal folds could be formed by deep-seated transcurrent movement along either of a pair of conjugate shear zones. If in the first case the central, easterly-trending portions of the anticlinoria are assumed to represent the zone of maximum deformation and rotation, then the central cordilleran anticlinoria would be likely to be situated about an easterly-trending shear zone along which the lateral movement was in the sinistral sense. If, however, the external northwesterly trending segments of these anticlinoria are assumed to represent the zone of maximum deformation, the transcurrent movements at depth would be in the dextral sense and trend in a northwesterly direction.

I suggest that in the central cordilleran anticlinoria the former case is the more likely; i.e., sinistral deep-seated shearing played the principal role in the deformation of the area and the conjugate, dextral shears are of secondary importance. This judgment is based first on the en échelon relationship of the two anticlinoria and secondly on an appraisal of the regional deformation patterns which are developed throughout western Papua and New Guinea. The regional role of horizontal movements will be examined in Section 3.2.

Figure 20 also illustrates the hypothetical stress pattern corresponding to the pattern of deformation of the central cordillera. However, due to the anisotropic properties of the rocks and their variation with depth, there is considerable latitude in assigning a stress field to a given strain pattern, thus, this can only be considered as a tentative approximation of the stress

conditions which operated in the central cordilleran region.

Judging from these stress-strain patterns one may say that the main tectonic elements, particularly the faults, in the central cordillera have suffered a substantial component of compressive stress. This is particularly true of the northwesterly-trending segments. The more easterly-trending sectors would be expected to show an important component of sinistral translation because on the stress diagram they lie in the middle ground between the shear and compression directions of failure. However, I must emphasize that although I speak of compressional stresses playing a role in the development of the central cordillera, it is a secondary role superimposed on structures related to a generally rising orogenic zone. This uplift is thought to be caused by processes quite independent of shearing at depth and its compressional surface expression. Nevertheless, these compressional stresses undoubtedly enhance the vertical growth of the orogen. But to what extent is one of the major problems to be solved in relation to transcurrent movements as an active agent in the development of an orogen.

2.3 CENTRAL FOOTHILLS FORELAND FOLDED BELT

The central cordilleran anticlinoria are bordered on the south by the Plio-Pleistocene folded belt (Plate 1) which forms the central foothills region of western Papua. The morphology of these structures is quite different from that of the central cordillera. In contrast to the broad arching structure of the Kubor and Bismarck anticlinoria the folds of the foreland belt are much smaller and form a continuous, often highly faulted belt flanking the central cordilleran region. To the best of our knowledge it appears that these foreland structures are the result of a discrete, relatively short-lived episode of deformation which occurred during the Pliocene and Pleistocene. This of course contrasts to the prolonged, complex history of the development of the central cordillera anticlinoria. Nevertheless, despite the rather profound differences in morphology and history, I suggest that these structures are the result of the same primary orogenic processes; i.e., differential vertical movements of the crust. However, as we shall see, these foreland structures may well be considered as a secondary effect of such uplift. There is the possibility that deep-seated horizontal movements may have also played a considerable role in the development of the foreland structures.

2.3.1 Structure

Several morphological subgroups can be recognized within the realm of the foreland belt. It is likely that these differences may be of considerable genetic importance, therefore, the foreland belt shall be subdivided on this basis for description.

It has been stated in a previous section that the foothills belt is separated from the central cordillera anticlinorial zone by a belt of volcanoes extending from Mt. Rentoul on the west to Crater Mountain on the east, a distance of about 230 kilometers. The volcanic accumulations associated with this volcanic zone mask the structural transition from the cordillera to the foothills. Perhaps the best structural connection can be made in a section which extends southwestward from the Mount Hagen area to the northernmost edge of the foreland belt at Mendi. Rickwood (1955) suggests the structure in this transition zone to be a broad synclinorium of Miocene and older rocks (Plate 5a). This region corresponds to part of the Miocene Kaugel trough as described in Section 1.5.

These northernmost structures of the foreland belt exposed in the Mendi region (Wage-Iaro zone) are a structural entity which is distinct from other well known structural subzones within the foreland belt.

Wage-Iaro zone.-- The Wage-Iaro zone is a triangular area situated southwest of Mendi (lat $6^{\circ}10'S.$; long $143^{\circ}40'E.$) between the Wage River in the west and the Iaro River to the east (Plate 1, Map 1). Structurally it represents a transition between the central cordilleran anticlinoria to the northeast and a highly imbricated

zone of the foreland belt to the south. The Wage-Iaro belt is developed in rocks ranging in age through Cretaceous to Upper Miocene. The style of folding and faulting is typical of a foreland belt. The anticlines are not highly faulted and have a marked asymmetry away from the heart of the orogen; i.e., to the southwest. There is some indication of low-angle thrusting which places Lower Miocene and Eocene rocks into juxtaposition with Upper Miocene rocks. Outstanding structures in the area include the Mendi, Ka, Nembi and Augu anticlines (Plate 1, (7,8,9)). The region east of long 144°E . and along the strike of the Wage-Iaro zone has not been mapped. There is some suggestion, however, that this structural belt may extend as far east as the Pio River area, and there may be represented by the Erun, Ormo and Ibia (Plate 1, (10,11,12)) anticlines.

Kutubu-Sireru imbricate belt.-- The Kutubu imbricate belt is the term applied to a 200-kilometer-long zone of quite intense faulting and folding which extends from beneath the volcanic mantle of Mounts Sisa and Rentoul (ca. lat 6°S .; long 143°E .) and which trends first south-eastward and then east-southeastward through the Erave River area to the upper Sireru River area, a distance of about 200 kilometers. Throughout most of its length the zone is about 40 kilometers wide. To the southeast it is bordered by the Darai Hills. The northern margin of the imbricate belt is obscured by the volcanic mantles of Mounts Rentoul, Giluwe and Ialibu, except in the extreme west where it borders the Wage-Iaro zone.

The imbricate belt is developed almost entirely in Lower to Middle Miocene rocks. It is characterized by a series of closely spaced faults and associated folds.

III.

STRUCTURE OF THE PAPUAN FORELAND FOLD BELT

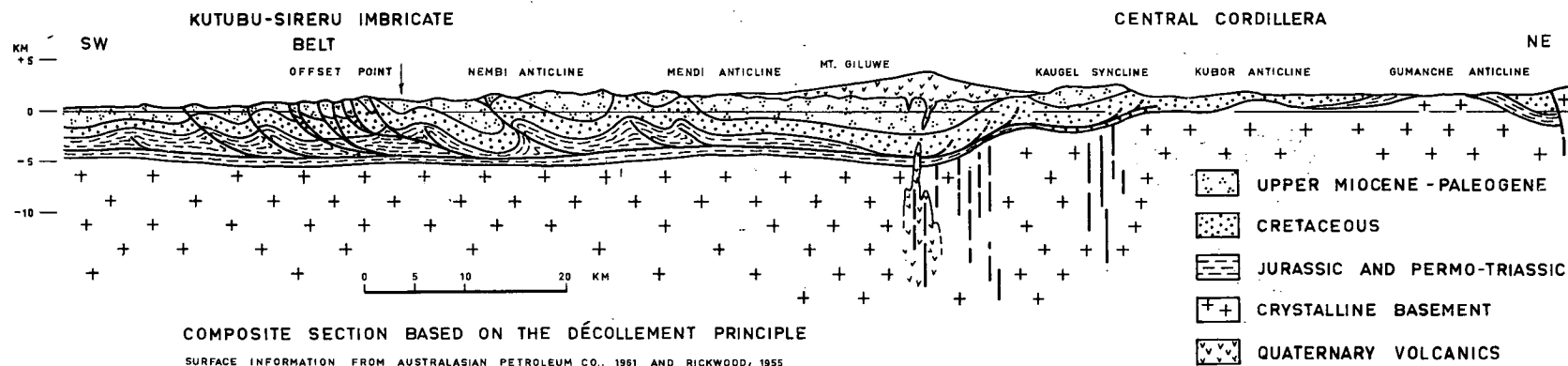


Plate 5a

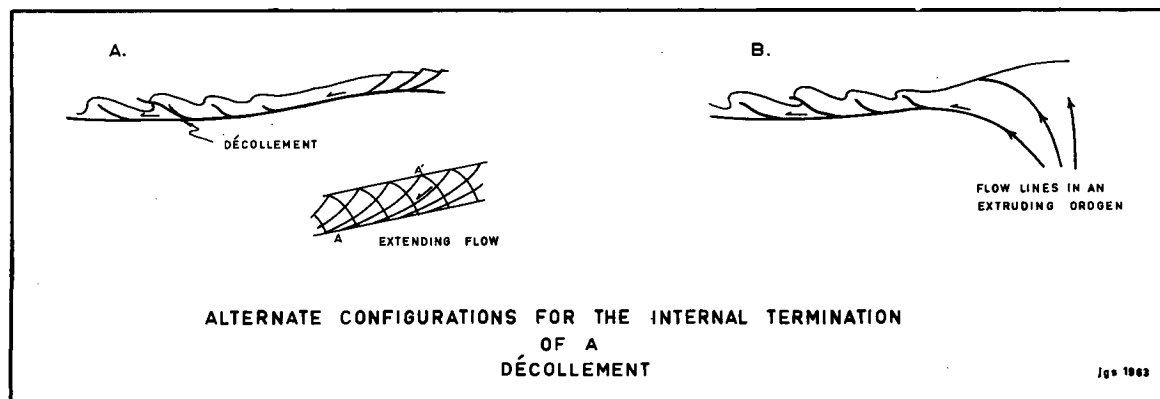


Plate 5b

The faults have very steep dips and for the most part have throws in the order of 1500 to 2000 meters. Several of the faults are nearly 90 kilometers in length. The general consensus of opinion is that they are high angle thrusts which flatten with depth but involve basement rocks (Australasian Petroleum Co., 1961; Plate 2). R.E. Linton (KRB, 1958), however, suggests that many of these faults, if not all of them, can be equally well explained as normal faults. I agree that at a local level it is possible to interpret these faults as being normal faults but at a regional scale, taking the rest of the structural pattern into consideration, it is more likely that these faults are thrusts.

There is also a possibility that an important element of transcurrent movement is associated with this fault zone. No such movement has been demonstrated in the field, but, as is usual with large zones of lateral faulting, much of the displacement is parallel to the grain of the country and detection by normal field methods would be difficult. The problem of transcurrent faulting in the foothills belt will be further examined in the succeeding pages.

Puri anticline.-- The Puri anticline and its associated structures; the Kereru, Era, and Kuku faults (Plate 1, (13,15,16)), occupy a general anticlinal belt about 10 kilometers wide situated on the eastern edge of the central foothills region. This belt is bordered on the south by the monoclinical rim of the Delta embayment and on the north by a synclinal belt of Upper Miocene and Pliocene rocks. The anticlinal belt itself is developed in Cretaceous through Upper Miocene rocks. This area,

because of its good petroleum prospects and relatively easy access, has been studied in some detail and the resulting information offers considerable insight into the structure of the foreland folded belt.

The Kereru anticline (Plate 1,(14)) is the westernmost structure of the system. It emerges from beneath the volcanic mantle of Mount Favenc and trends east-southeastward beneath the Era River. The western end of the Kereru anticline is strongly deformed by the steeply dipping, east-southeast-striking Kereru fault system which places Cretaceous rocks in juxtaposition with Middle and Lower Miocene rocks. Twentyfive kilometers to the east the Kereru fault joins the Era fault, which separates the Kereru-Puri anticlinal belt from the homoclinal belt to the south.

The Puri anticline lies to the northeast and en échelon with the Kereru anticline. Beginning just west of the Era River and north of the plunging nose of the Kereru anticline, the Puri anticline strikes east-west for about 20 kilometers then turns sharply to the southeast through an angle of about 35 degrees. To the south the Puri anticline is separated from the homoclinal rim of the Delta embayment by first the Kuku fault and then the Era fault, which eventually join and swing southward parallel to the edge of the Delta embayment.

In the course of drilling the Puri well the bore passed through a horizontal fault surface at 2250 meters and re-entered early Lower Miocene limestones which were first encountered at about 550 meters. On the basis of this information the Puri anticline has been interpreted

as a steeply asymmetric anticline with a thrust faulted core (Plate 4). Furthermore, the Era and Kuku faults are believed to be the surface expression of the major thrust revealed at depth in the Puri well.

There are two possible interpretations of the Puri-Kereru anticlinal system each of which have quite different tectonic implications. On one hand there is the possibility that the faults are generally steep reverse faults that involve basement rocks. As I previously mentioned such an assumption has been made by Australasian Petroleum Company workers for the imbricate belt to the west. Lees (1952) favored this type of interpretation of foreland belts in which the sedimentary cover accommodates itself to the basement. The second possibility is that the Kuku and Era faults are slices which bifurcate from a basal, sole thrust or décollement which exists at depth. In the case of the Puri well the fault encountered at depth might represent part of such a décollement. The relative merits of these two interpretations will be examined in more detail in a subsequent section.

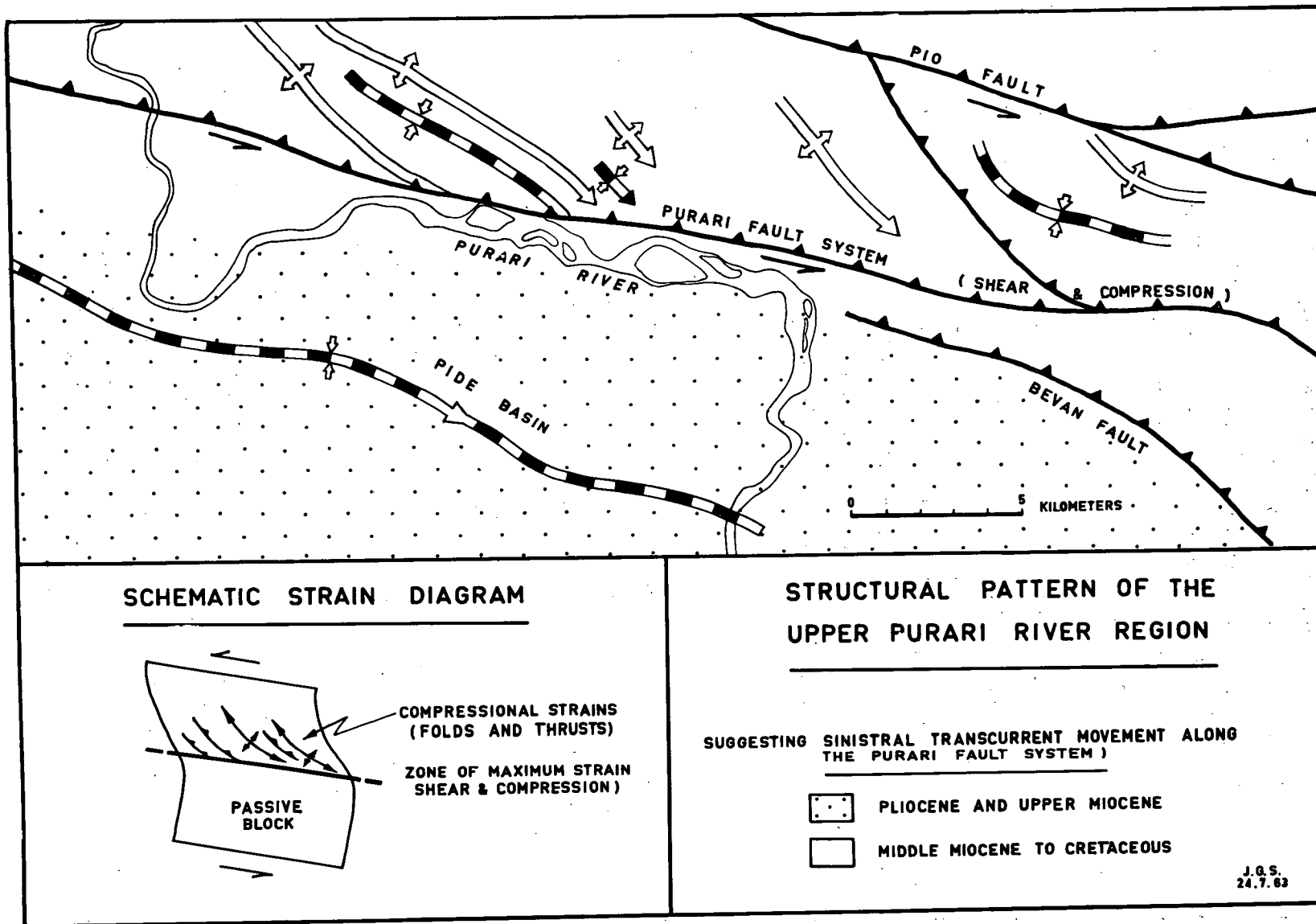
Pide synclinorium.-- The Pide synclinorium lies between the Puri anticline and the Bevan fault to the north (Plate 1,(17)). It is the largest and westernmost structural basin in a series of basins which parallel the northern and eastern margins of the Delta embayment. The basin is developed in Upper Miocene and Pliocene rocks. Other basins in the belt, which is bordered on the north by the Bevan fault and on the south by the Kuku fault, includes the Mena, Kuku and Goigi basins.

The Pide basin is 40 kilometers long and 15 kilometers wide. There are several minor folds within the main synclinorium. In addition to these the western end of the basin is divided by the Bwata anticline. This anticline was drilled in the search for oil and in the course of drilling was found to be asymmetrical to the south. The core is cut by several minor thrust faults which appear to have no surface expression. Possibly these faults represent splays off the Bevan fault or, less likely, the Kuku fault in a manner similar to the Kereru-Era relationship.

Pio-Purari Dividing Range.-- The Pio-Purari Dividing Range (ca. lat $6^{\circ}50'S$.; long $145^{\circ}E$.) appears to be one of the most structurally complex and tectonically active areas of the central foothills region. Carey (LI, 1941) as well as Kent and Rickwood (LW, 1956) have examined the area and have given accounts in their reports for the Australasian Petroleum Company.

The gross structure of the area is a northwest-striking anticlinorium 15-20 kilometers broad and 50-60 kilometers long which has Cretaceous rocks exposed in its core. This anticlinorium is complicated by a considerable number of faults with rather divergent trends. The Purari fault zone (Plate 1, (21)) is perhaps the most important of these faults. It strikes nearly east-west and forms the southern margin of the Pio-Purari structural province separating it from the less complicated Pide basin to the south (Fig. 22). The Purari fault is apparently continuous with the eastern end of the Kutubu-Sireru imbricate zone. From the upper Purari River area the fault zone trends eastward for 60 kilometers to the

Figure 22



Eri River area where it abruptly changes strike to a more southeasterly trend and swings in a great arc to intersect the Aure fault (Plate 1,(20)) near the junction of the Aure and the Purari Rivers. Throughout this latter region the Purari fault zone forms the northeast margin of the Purari syncline.

Carey (LI,1941) suggested that the Purari system is a belt of important thrusting. The linear nature of the zone and gross disregard for topography as well as its relation to adjacent anticlines indicate that there may also be an important element of transcurrent movement along the Purari fault, a possibility which will be considered in the following section on the mechanics of tectogenesis.

Along the western part of the Purari fault system (west of long 145°E.) a series of northwest-trending anticlines and faults branch off the north side of the fault at angles of about 40 degrees. Indeed, the main anticlinal axis of the Pio-Purari Dividing Range is at a considerable angle to the Purari fault. These relationships; namely, the intersecting trends, are indicative of lateral movements and more specifically indicate a considerable component of sinistral movement along the Purari fault zone.

The northern margin of the Pio-Purari Dividing Range is made by the Pio fault which emerges just south of the volcanic mantle of Mount Karimui. It strikes southeastward until it intersects the Hau-Toila fault zone (Plate 1,(23)) in the Upper Pio region. Carey (LI,1941) has interpreted the fault as a thrust.

Aure-Tsoma region.-- The structures of the Aure-Tsoma region together with those of the Pio-Purari Dividing Range constitute a complex structural knot between the easterly-trending structures of the central foothills region and the northerly-trending structures of the Kukukuku lobe (Fig.23). The Aure-Tsoma structural province is a wedge-shaped area defined by two major fault systems; the Aure fault and the Hau-Toila fault zone. Both these fault zones have played an important role in the structural development of Papua.

The Aure fault was first recognized by Carey (LI, 1941) just east of the Purari River near McDowal Island where Eocene limestones were found in juxtaposition with Muruan rocks indicating a stratigraphic throw of probably no less than 3000 meters. In this area the fault trends nearly north-south and was interpreted by Carey as a thrust. Subsequently, he traced the fault to the Purari-Aure River junction where the fault changed to a northeast trend, paralleling the Aure River valley for at least 40 kilometers. It is this latter northeast-trending section of the Aure fault which is of considerable interest in this discussion.

Since the northeastern extension of the Aure fault is nearly at right angles to the lower Aure fault it is unlikely that it has the same nature of movement; i.e., it is probably not a thrust fault. It is more likely that there is considerable lateral movement along the fault, probably in the dextral sense. Similar relations between thrusts and wrench faults have been observed elsewhere, particularly in the Jura Mountains. It is also possible that there may be an important element of tension

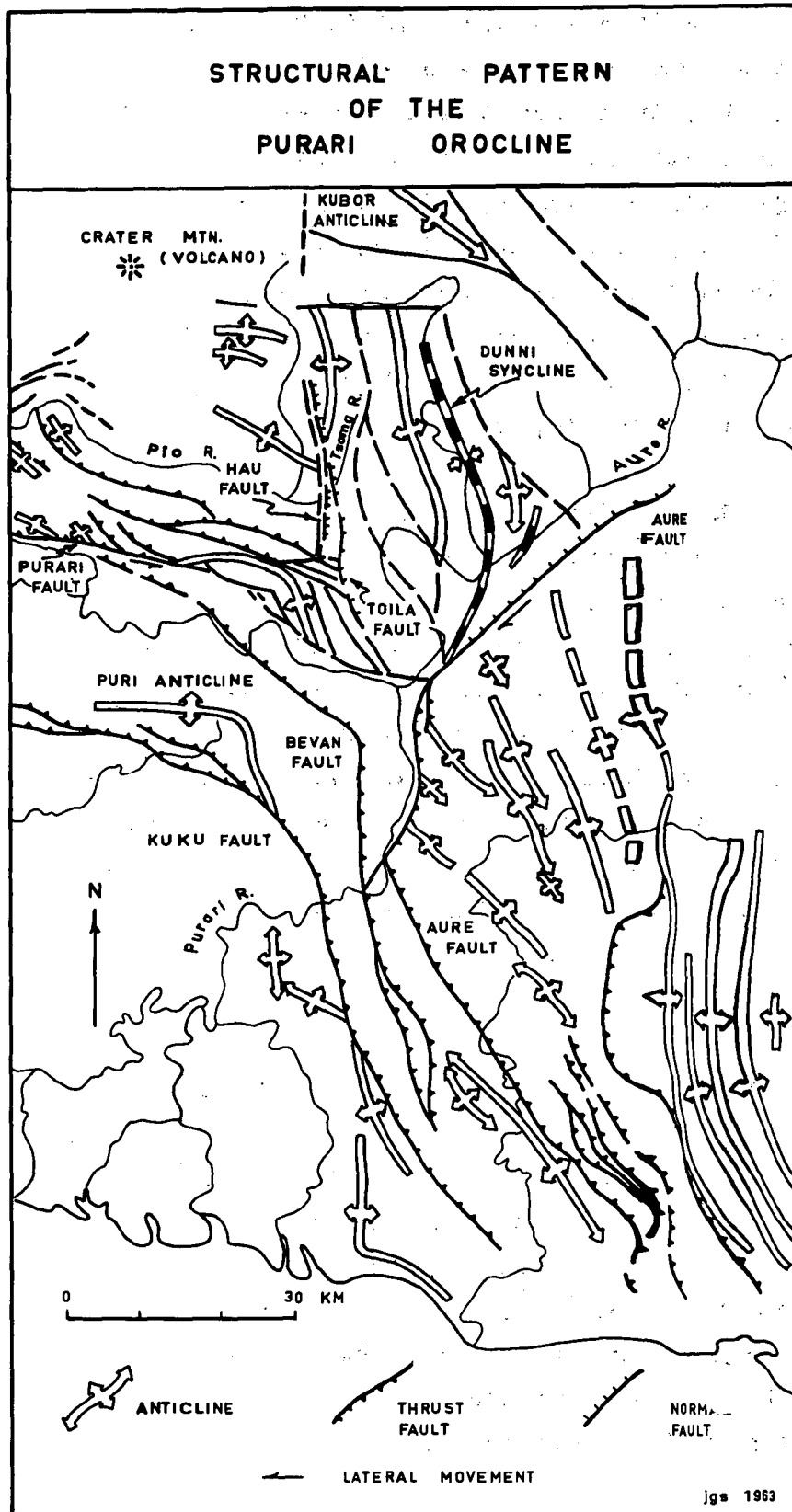


Figure 23

along the Aure fault. The likelihood of these two possibilities will be considered more thoroughly in Section 3.3.2.

The western edge of the Aure-Tsoma structural province is defined by the Hau-Toila fault zone. This fault zone was described by Kent and Rickwood (LW, 1956). The Hau-Toila fault zone terminates against the Purari fault west of the Aure-Purari River junction. From this point it trends essentially north and crosses into the Territory of New Guinea near the junction of the Pio and Tsoma Rivers. In this sector the faults have an important element of dip slip movement with the down-thrown side to the east. Farther north the fault zone is contiguous with the north-trending Tsoma anticline which appears to be a flexure related to the fault zone.

The most interesting aspect of the fault-flexure zone is its relationship to the structural trends immediately adjacent to it. To the west the structural grain of the region is east-west and at least four anticlines are truncated abruptly by the Hau-Toila zone. To the east the structural grain parallels the fault zone; i.e., north-south. These latter northerly-trending structures, which lie between the Hau-Toila and Aure faults, are considered by Kent and Rickwood to be the continuation of the northerly structural trends in the Kukukuku lobe. The anticlines in this wedge-shaped zone have very narrow, pinched cores and are in general highly sheared along the crests. In contrast the synclines are quite broad and apparently not strongly deformed so that in cross section the folds have a catenary form. In plan the pattern of these structures is also quite peculiar. All the

structures: Habidebidi and Baimoi faults, the Hasa anticline, the Dunni syncline and others, including the main boundary fault system, originate and branch north-northeastward from a common center near the junction of the Aure and Purari Rivers. Some 50-60 kilometers to the north, these structures with the exception of the Aure fault, are truncated abruptly by the east-west to southeast-trending structures including the Gorga fault and the easternmost extension of the Kubor anticline.

I interpret the Aure-Tsoma region as a wedge-shaped graben and believe that it is probably related to considerable rotational movements of the crust. More will be said of this later.

Kuru basin.-- The structures described in this section lie within an oblong east-trending basin, developed in folded Pliocene and Upper Miocene rocks, which is situated south of Mount Duau and Favenc. The western end of the basin is closed; the eastern end opens to the Delta embayment. Anticlinal structural elements in this basin include the Kuru, Sireru and Wana anticlines (Plate 1, (27,28,29)).

The Kuru anticline has been mapped and drilled in the search for petroleum and is the best known structure in the region. Drilling has shown the internal structure of the anticline to be quite complex; the core is highly faulted and possibly diapiric.

The Wana anticline, which was detected by seismic methods and subsequently drilled, is from all indications a symmetrical and uncomplicated structure. It is possible

that it is the continuation of the Orie anticline.

2.3.2 Origin of Papuan Foreland Folding

The morphology of the Papuan foreland folded belt might be explained by either of two basic tectogenic mechanisms. One alternative is developed in a series of cross sections that was published by the Australasian Petroleum Company (1961). Their interpretation of the foreland structure was based on the assumption that somewhat wedge-shaped slices of the crystalline basement are the active agents in the production of the overlying folds. This is the concept of foreland folding strongly advocated by Lees (1952) and many others; namely, that the cover of sedimentary rocks in the foreland zone plays a passive role and accommodates itself to movements of the basement beneath. I have compiled a composite structural section based on this principle which extends across both the foreland belt and the central cordilleran region (Plate 4b).

However, there is an alternate interpretation of the foreland folded structures that is based on the Abscherung or décollement principle of Buxtorf (1910). I have also prepared two composite structural sections across the foreland and central cordillera according to this principle, and it will be seen that all of the structures of the foreland disturbed belt can be explained quite adequately by the décollement principle. In the following paragraphs I will examine both these mechanisms of folding in cognizance of our knowledge of the foreland structures and point out the adequacy and inadequacies of both these schemes.

Basement wedge principle.-- Plate 4b is a composite

cross section drawn across the entire foreland and cordilleran zones of the New Guinea orogen and is based on the principle of basement faulting movements as the active mechanism of foreland folding. In general the distribution and morphology of the folded belt is quite compatible with this scheme. This is particularly true when one considers the relationship between the folding mechanisms of the foreland and the cordilleran region. As we have just seen the structure of the central cordillera can be best explained by differential vertical movements of fault-defined crustal blocks. Hence, the basic mechanism of folding in the two regions would superficially appear to be very similar.

The structural development of the Pio-Purari region to some extent also favors the basement-wedge hypothesis of foreland folding. The development of the Purari fault system is particularly relevant. In the first place there appears to have been considerable vertical movement along the Purari fault as it places early Cretaceous rocks into juxtaposition with Middle and Lower Miocene. In general it separates two highly contrasting structural units: the complex folds of the Pio-Purari Dividing Range and the gentle Pide basin to the south. In the second place it will be shown that there has been considerable transcurrent movement along the Purari fault as indicated on Figure 22. Such vertical and horizontal movements would be quite compatible with the deep-seated faulting as a controlling mechanism of foreland folding.

Décollement principle.-- Plates 4a and 5a are composite sections of the Papuan foreland and central cordillera which have been drawn on the assumption of the décollement

principle. Note that Plate 4a crosses the same region shown in Plate 4b; consequently the relative merits of the two constructions can be seen easily.

Every feature of the Papuan foreland folded belt is consistent with *décollement* principle. In other words the morphology and historical development of the foreland belt are consistent with the deductions one would make if the *décollement* principle was assumed. One of the most important general arguments supporting the *décollement* principle is the fact that concentric folds, by virtue of their geometry, die out at depth and imply the presence of a *décollement* or detachment beneath the folded sedimentary sequence at a depth governed by the size of the folds. Carey (1962) has emphasized this point. Then the problem becomes whether or not the deformation of the foreland belt fits or approaches a concentric model. Although there has been no really detailed study of the nature of folding in western Papua from this point of view, in general it does appear that many of the folds conform closely to the concentric pattern. This is especially clear in the Wage-Iaro zone where the folding is not highly complicated by faulting. In the Kutubu-Sireru imbricate belt the faulting is so intense that it would be nearly impossible to construct these structures according to a concentric model. However, it is quite likely that the imbricate faults developed due to "over-folding" and rupturing of originally concentric folds. If in fact the folds and faults of the foreland belt tend toward the concentric model, and there is good suggestion that they do, then a *décollement* must occur beneath the folded belt at a depth controlled by the geometry, particularly the amplitude, of the folds.

Such a *décollement*, as applied to the Papuan folded belt, is illustrated on Plates 4a and 5a. These sections have been constructed by concentric methods, taking into consideration the regional variations in sedimentary thickness as described in Sections 1.2 to 1.7. On the basis of these cross sections, it is most likely that a volume deficiency and the resulting *décollement* would be developed in the Mesozoic levels of the stratigraphic sequence. In particular the Jurassic rocks would have provided an ideal zone for the development of a detachment surface, since they are composed mainly of incompetent shales and mudstones which would have offered little resistance to sliding and folding of the overlying allochthonous sheet. Interstitial fluid pressures within the sedimentary sequence may have also played an important role in the formation of the *décollement* (Hubbert and Rubey, 1959).

Referring to Plate 4a it can be seen that the flat fault encountered in the Puri bore is compatible with the presence of a *décollement* within the Mesozoic. Certainly the form of the Puri anticline for the most part conforms rather well to the concentric pattern and consequently necessitates the presence of a *décollement*. The pronounced asymmetry of the anticline is especially well explained by the *décollement* principle.

In earlier paragraphs I mentioned that the Purari fault region fitted particularly well with the basement-wedge scheme of foreland folding. Plate 4d indicates that in terms of vertical movements this and other structures can be equally well explained by the *décollement* idea. In either hypothesis the magnitude of the vertical

movements in this region is very large and its significance is as yet not fully understood.

To reconcile the apparent transcurrent movements associated with the Purari fault and the décollement principle, a zone of rather important deformation must, nevertheless, be admitted to exist in the basement beneath the detached sheet in the Pio-Purari region. However, in this case the movement would be almost all horizontal with little or no vertical movement. The nature of this faulting will be discussed shortly.

At present it is impossible to prove conclusively whether the décollement process or basement faulting has been the active agent in the Papuan foreland folding. Eventually the problem may be solved by deep drilling of the folds in the search of petroleum. I favor the décollement principle but certainly do not deny the existence of important basement faulting beneath the folded belt. However, such faults are envisioned to be similar to the Komewu fault and the other great fractures which are thought (Section 3.1) to have defined the intrageosynclinal troughs and geanticlines, and to have accommodated the vertical movements of these principal diastrophic elements over a considerable period of time. As mentioned in Sections 1.2 and 1.9, the foreland folds developed in a relatively short interval of time and are considered to be the secondary manifestation of the differential vertical movements accompanying orogenesis. Specifically, the foreland folds are regarded as having formed as a result of gravitational gliding off the flanks of the rising central cordillera anticlinorium; a mechanism which requires the development of a décollement.

Thus in a broad sense basement faulting has had a decisive role in the foreland folding in that it defined the rising orogenic nuclei (i.e., primary tectogenesis); but it is probably not related in the commonly accepted sense; viz., that each foreland fold or group of folds is produced by a particular fault-defined basement wedge.

There are still some points to be discussed which are particularly related to the décollement principle of foreland folding. One of the most interesting problems associated with the gravitational gliding-décollement mechanism of folding is how the décollement terminates, perhaps I should say originates, in the central zone of the orogen. At least two solutions are possible. The first is that maintained by de Sitter (1959) among others. In this case the décollement or basal detachment plane of the gliding sheet would emerge high on the flanks of the uplifted mass. It is likely that the décollement would emerge along a series of slip surfaces which are concave upward. This movement can be represented by a slip-line field comprised of two families of curves drawn so that their directions at any point give the two perpendicular direction of maximum shear stress. Nye (1952) stated that this kind of movement, which he called "extending flow", is common to glaciers. It should be noted that the family of curves AA' (Plate 5b) coincides closely to the configuration that would be naturally assumed by the layering of a sedimentary sequence developing in a geosynclinal trough (Kaugel trough) adjacent to a geanticlinal high. Consequently, movement along the décollement is likely to be relieved along such shear directions on the upper flanks of the actively rising structure, in this case the central cordilleran massif.

De Sitter states that an appropriate slope must be recognised in the field to account for any gliding of this type. Certainly such a slope is present along the southern margin of the central cordillera as can be seen in Plates 4a and 5a.

The second alternative solution to the décollement problem has recently been suggested by Carey (1962) who believes that in many cases the décollement turns downward into the axial zone of the orogen and is thus intimately related to the fan-like flow pattern of the "regurgitation" orogen. The driving force of gliding is provided by the pressure gradients resulting from outflow of the geosynclinal sediments during orogenesis. Consequently, tectonic transport may be in the direction opposite to the regional slope of the décollement.

Because of the nearly complete lack of detailed information along the southern flank of the central cordillera, which is for the most part masked by Quaternary volcanics, it is impossible to solve this problem. Certainly there is no direct evidence for or against either hypothesis. In Plates 4a and 5a I have illustrated the décollement configuration advocated by de Sitter.

History of movement.-- It has been shown that vertical movements were active in the geanticlinal regions of the Papuan geosynclinal system as early as the Mesozoic. However, during the Middle Miocene uplift began to dominate over subsidence and this tendency continued throughout the Upper Miocene. The rate of uplift apparently increased during the Pliocene and Pleistocene and it was then that the folding in the Papuan foreland

had its inception. In the process of this uplift, which appears to have been most intense in the central cordilleran region, the Kaugel intrageosynclinal trough was tilted southward. A considerable thickness of Tertiary and Mesozoic rocks had accumulated in this trough and these began to spread southward in response to the uplift. Many of these sediments, especially the Tertiary, probably contained very considerable amounts of interstitial water which enhanced their outward movement. The apparently incompetent nature of the basal units in the Jurassic shales and mudstones would also facilitate such movement and hence, it is likely that the gliding sheet moved along a *décollement* somewhere within the Jurassic or possibly the Cretaceous. Furthermore, as this sheet moved southward it was strongly folded, because the rocks near the front of the gliding mass were moving at a slower rate than those higher on the flanks of the rising central uplift. Folding was likely to have been enhanced by differential rates of flow parallel to the internal layering of the allochthonous sheet of geosynclinal sediments.

I have already pointed out the very close spatial coincidence of the imbricated foreland belt and the position of the Lower Miocene Erave-Wana geanticlinal swell. In this zone for one reason or another the *décollement* surface emerged as a series of splays and gave rise to the highly imbricated Kutubu-Sireru belt. This imbricate belt represents the frontal zone of the gliding mass. The forward movement of this zone was probably retarded by the reverse gradient on the north side of the Erave-Wana swell which gave rise to the "piling-up" of the imbricate structures. Flow in this

zone was similar to the pattern of compressive flow occurring in glaciers (Nye, 1952). The southwestward progression from the more open structures of the Wage-Iaro zone to the highly disturbed imbricate belt is quite clear on Plate 5a.

Another factor contributing to the imbrication is associated with the considerable thinning and facies change of the Lower and Middle Miocene rocks developed on the Erave-Wana swell (Figs. 6 and 8). This thin rock sequence may not have been able to bear the considerable stress conveyed to it by its thicker and more mobile counterparts in the Kaugel trough and, as a consequence, failed by rupture rather than by flow.

Thus, in general, it can be seen that the form of the foreland folded belt is closely associated with the diastrophic framework of sedimentation in the Papuan geosynclinal region, particularly that of the Lower and Middle Miocene.

Role of horizontal movements.-- It has already been suggested that deep-seated sinistral transcurrent movements are likely to have played an important role in the diastrophic evolution of the central cordilleran region. I am convinced that in addition to vertical movements of the crust, horizontal movements are expressed in the evolution of every structural province in New Guinea. This theme will be developed further in Section 3. Here the particular problem is to bring attention to the features which suggest that transcurrent movements may have had a role in the Plio-Pleistocene deformation of the foreland disturbed belt.

However, before the folded belt is examined for evidences of transcurrent movement, it must be understood that there are, undoubtedly, rather basic differences in the manifestation of transcurrent movements in this zone as in contrast to similar movements in the central cordillera. This difference is again founded on the contrasting historical developments of the two regions and on the relative rates of foreland-type folding versus deep-seated transcurrent shear deformation. As Carey (1962b) has pointed out, transcurrent movements are of a very secular nature and often influence the entire diastrophic cycle of an orogenic region. Folding movements of the foreland-type, however, are rather episodic in character and develop within time limits several orders of magnitude shorter than "fundamental" transcurrent faults. Hence, it is possible that the effects of these transcurrent movements are often concealed by the more superficial effects of the foreland folding. Nevertheless, the transcurrent movements are propagated slowly but relentlessly through the overlying cover of folded sediments and contribute to their deformation. Movements of this kind can often be detected by detailed study of the peculiarities in the pattern of folding. Such study has lead me to believe that important deep-seated transcurrent movements were in progress during the deformation of the foreland folded belt.

Important wrench faulting has never been observed in the Papuan folded belt, but this is not unusual considering the reconnaissance nature of most of the mapping and the obstacles presented by the rugged jungle conditions. However, lateral movement is suggested in several localities by the pattern of folding and faulting;

i.e., the configuration of individual folds and associations of structures. The most outstanding example of this latter type is developed in the upper Purari River region. Here the relationship of the Purari fault system and the adjacent folds and faults to the north are strong indications of such transcurrent movement. Along the entire length of the Purari fault (Fig. 22) a series of en échelon anticlines, synclines and faults splay off the main fault at angles of 30 to 40 degrees. Similar patterns of folding and faulting are developed in southern California where they are clearly associated with transcurrent movement along the dextral San Andreas fault (Newport-Inglewood belt; Reed and Hollister, 1936). I am confident that the structural pattern in the Purari region had a similar origin, although in this case the movement has been in the sinistral sense and is thus consistent with movements suggested by the pattern of folding in the central cordillera. The mechanics of this deformation is shown schematically on Figure 22.

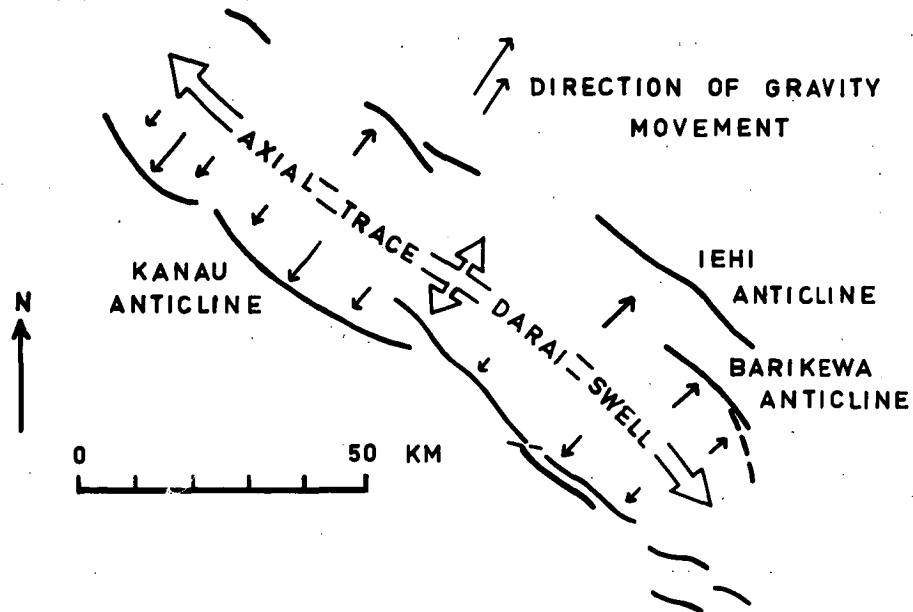
2.4 DARAI SWELL AND RELATED STRUCTURES

The highly disturbed Kutubu-Sireru imbricate belt is separated from the Fly-Digoel platform to the southwest by a northwesterly-trending, broad (40-50 kilometers) swell or uplift lying between the Kikori and Turama Rivers (Plate 1). This feature has already been discussed in relation to its role in the Upper Miocene and Pliocene diastrophic framework of sedimentation. At that time it represented a rather peculiar emergent area of low relief situated between the Upper Miocene and Pliocene exogeosynclinal trough and the Fly-Digoel platform. It was also pointed out that this region coincides closely to the site of the Lower Miocene Omati trough where a great thickness (ca. 3000 meters) of limestone accumulated.

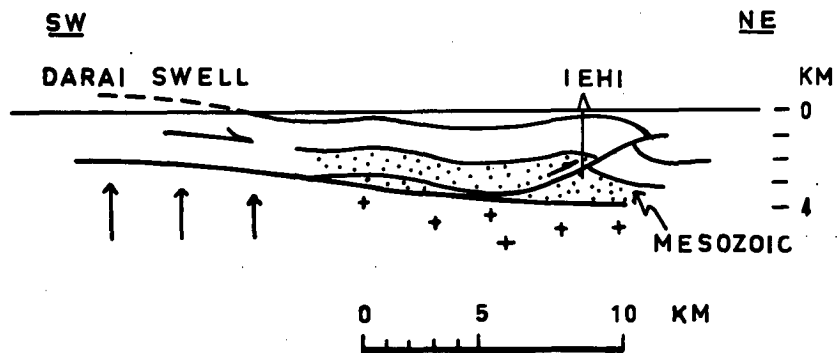
This particularly unique character apparently had a considerable effect on the behavior of the region during the Plio-Pleistocene stage of tectogenesis, as the pattern of folding associated with the swell contrasts with the deformation patterns developed in the main foreland belt. There are several subordinate anticlinal structures developed on the Darai swell (Fig. 24). The Iehi and Orié anticlines fall into this category and are transitional structures which separate the easternmost ends of the Kutubu-Sireru imbricate belt and the Darai swell proper. These anticlines are transitional in the sense that they

STRUCTURAL FEATURES SUGGESTING GRAVITY TRANSPORT OFF THE DARAI SWELL

A. PATTERN OF MARGINAL ANTICLINES



B. NORTHEAST FACING OF IEHI ANTICLINE



jgs 1963

Figure 24

are more strongly folded than the structures on the adjacent Darai swell but are not strongly faulted and cannot be included in the imbricate zone. The very gentle Barikewa anticline is considered as part of the main swell.

The Iehi anticline lies nearest the Darai swell just north of the Kikori River and the Barikewa anticline. The crestal trace has a slightly undulating but generally northwesterly trend throughout its 55 kilometers of length. It has a pronounced northeast facing; the northeast flank dips about 50 degrees compared to the relatively shallow 15 degrees on the southwestern limb. Moreover, drilling has shown a fault with 900 meters of vertical offset that has been interpreted as a thrust fault dipping steeply to the southwest. These features indicate that the direction of tectonic transport has been opposite to the sense of movement which produced the imbricate belt to the north; i.e., northeastward rather than southwestward.

The Orie anticline lies to the northeast of Iehi and is adjacent to the southern edge of the imbricate belt. It has a length of over 90 kilometers and a pronounced dextrally-coupled sigmoidal pattern. The anticline plunges eastward beneath the Delta embayment, and it is possible that the Wana anticline, which was discovered by seismic work and drilling, is a continuation of Orie. Like its neighbor, Orie has an anomalous northeast-facing asymmetry.

The northeast-facing asymmetry of these folds is out of character with the structural patterns displayed

by the other anticlines in the fore land belt and implies local northeastward tectonic transport. There are two possible mechanisms for such motion. The first and preferred alternate is that the asymmetries resulted from sliding and lateral spreading away from the rising axial zone of the swell. These are very gentle structures and could have easily originated in this manner, especially when we consider that the Darai swell has been a positive region since the Upper Miocene.

The anomalous asymmetries might also be explained if the décollement, that passes beneath the imbricate belt, curled up and back on itself. Similar reversals in local asymmetry have been observed in the Juras and are explained in this fashion. However, another argument in favor of the first alternative; i.e., gravity transport off the Darai swell, is the disposition of the anticlines which fringe the southwestern rim of the swell. From the northwest this belt includes the Kanau, Northwest Darai, Mid-Darai, Northwest Omati and Kahamoi anticlines. Both the Kanau and Northwest Darai anticlines have a marked asymmetry to the southwest indicating tectonic transport in that direction, possibly by sliding. Furthermore, in plan the Kanau anticline consists of two arcuate segments (25 and 50 kilometers in length), which are convex to the southwest. This festoon appearance suggests that the folds are due to gravity gliding and developed because the older, central portions of the anticlines moved farther down slope than the ends of the structures.

All these structural features suggest that, during the Plio-Pleistocene tectogenic phase of diastrophism,

the Darai uplift moved vertically upward as a more or less independent block and produced a pattern of folding unrelated to the foreland belt to the north. Again the basic framework of this block was probably roughed out during the Lower Miocene phase of geosyncline formation and probably is related to the Omati trough (Fig.9). The relationship between geosynclinal troughs and subsequent uplifts will be given considerable attention in Section 4.

2.5 WESTERN CORDILLERAN ANTICLINORIA

The western cordilleran region represents the third and final major structural province of the New Guinea orogenic system which will be examined in detail in this study. I have already described the external morphology of this very rugged mountainous region and in this respect the western cordillera is very similar to the central cordilleran region. Superficially these two regions are also somewhat similar from a structural point of view and it will be demonstrated that the tectogenic mechanisms were certainly similar; namely, primary vertical movements with a strong superimposed element of trans-current movement. However, the structural history of these two cordilleran regions appears to be quite different. The following discussion will be devoted to description and analysis of the morphological and mechanical similarities and historical dissimilarities in order to ascertain if and how the tectonic processes and manifestations might fit into an overall unified pattern of orogenesis.

2.5.1 Structure

The gross structure in the western cordilleran region is a series of three en échelon anticlinoria (Fig. 25). All these structures are bounded on the north by important, often imbricate zones of faulting and on the

TECTONIC PATTERN OF THE WESTERN CORDILLERA

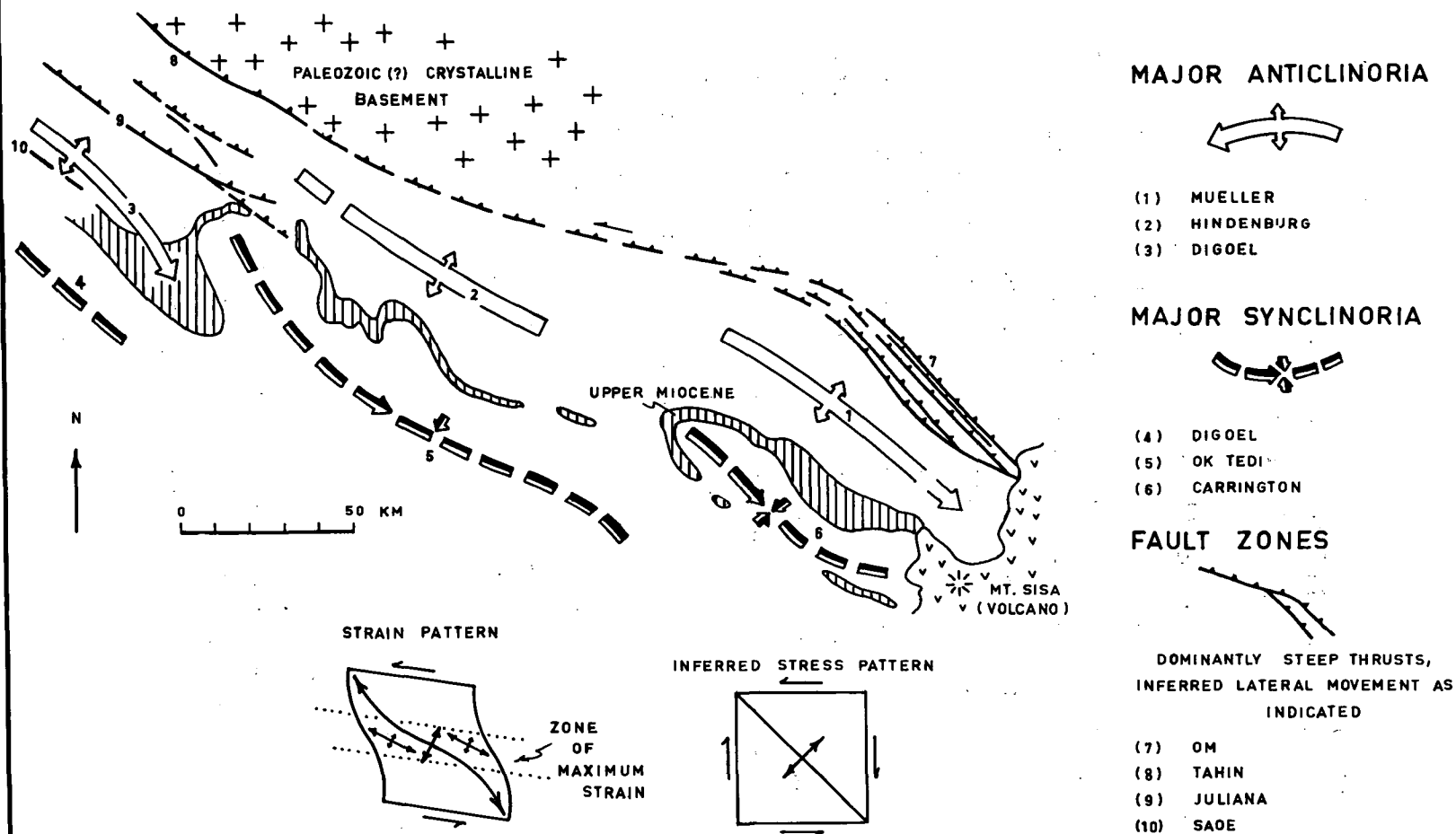


Figure 25

south by synclinal basins of gently folded Pliocene rocks.

Mueller anticlinorium.-- The easternmost structure commences at about lat 6°S. ; long 143°E. and trends northwestward through the Mueller Range to the Upper Strickland River area. This anticlinorium, which will be called the Mueller anticlinorium (Fig.26), is about 90 kilometers long by 30 kilometers wide. It is developed in mainly Lower Miocene and Cretaceous rocks and includes such subordinate structures as the Lavani, Koi'ange, Hides and Mueller anticlines.

The Mueller anticlinorium is bordered on the north by a belt of imbricate faults 10 kilometers in width which have been interpreted as steep reverse faults. To the north beyond this fault belt lies the uninvestigated Laigap River region; to the south the Mueller anticlinorium is paralleled by a broad synclinal structure, the Carrington synclinorium.

Hindenburg anticlinorium.-- The central anticlinorium in the group extends northwestward from the upper Strickland River area through the Hindenburg Range to beyond the junction of the West Irian, Papua and New Guinea borders. This second structure will be called the Hindenburg anticlinorium. Like the Mueller anticlinorium the Hindenburg arch is composed predominantly of Cretaceous and Lower and Middle Miocene rocks, but with minor Jurassic exposures as well. In addition to these normal sedimentary types, granodiorite is exposed in the core of the anticlinorium at its extreme northwestern end in the Antares Mountain area of West Irian. (Exposures of a similar granodiorite, but of a much more restricted area,

II. STRUCTURE OF THE WESTERN CORDILLERA

SW

NE

CARRINGTON BASIN.

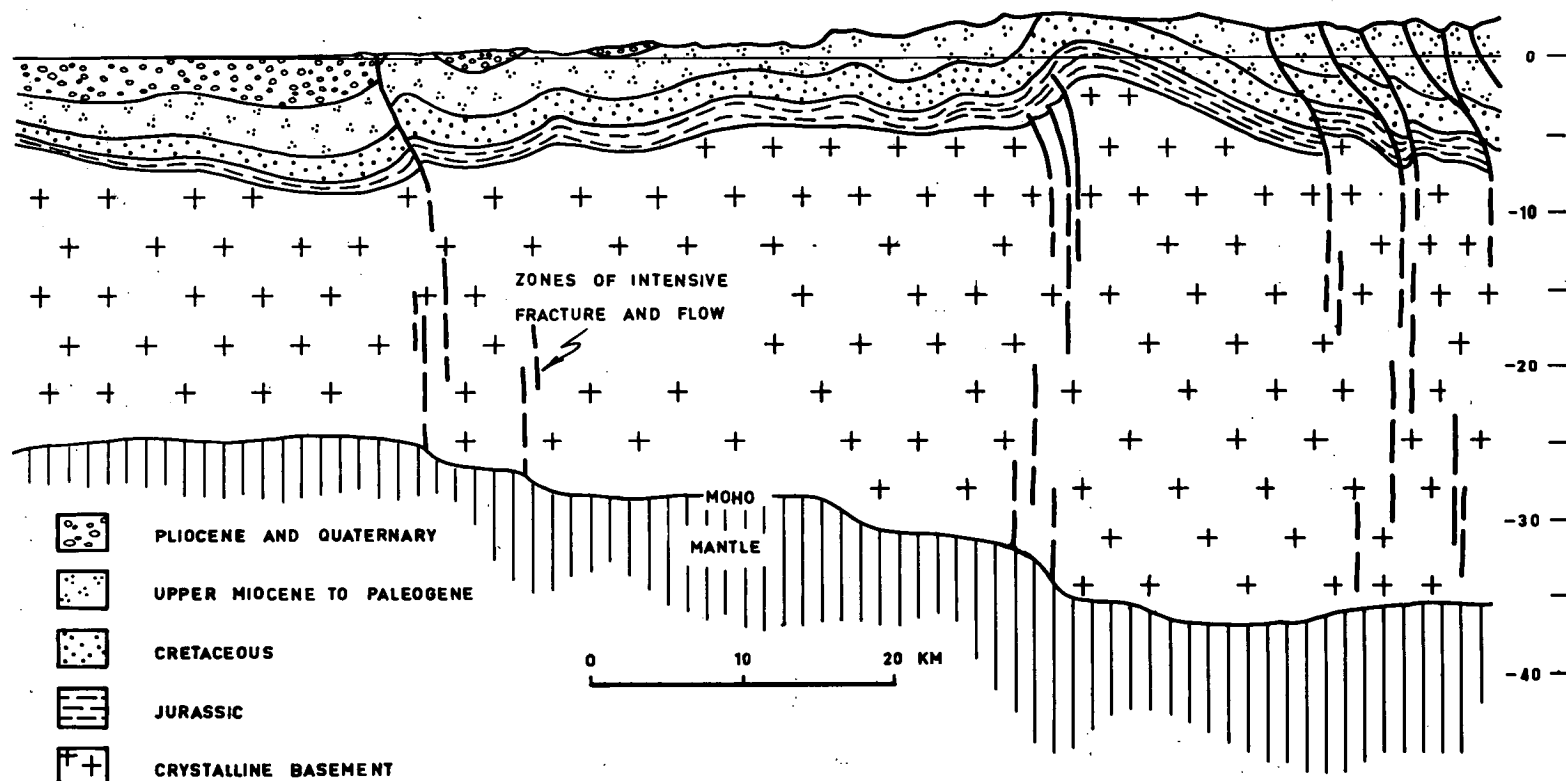
MUELLER ANTICLINORIUM

CECILIA ANTICLINE

LAVANI ANTICLINE

OM-TARI FAULT ZONE

KM
+5
0
-10
-20
-30
-40



SURFACE DATA FROM AUSTRALASIAN PETROLEUM COMPANY, 1981

J.G.S. 1983

Figure 26

are also found in the core of the Koi'ange anticline in the Mueller anticlinorium). In this area the Hindenburg anticlinorium is cut by a series of high-angle faults parallel to the main anticlinorial trend. The anticlinorium is bordered on the north by an important fault zone which Bär et al. (1961) have named the Tahin fault zone. This fault zone separates the sediments of the anticlinorium from an extensive Paleozoic (?) metamorphic terrain to the north in the Boendermaker Range. The Hindenburg anticlinorium is also bounded on the south by a gently folded basin consisting of Pliocene and Upper Miocene rocks.

Digoel anticlinorium.-- The third and westernmost of the anticlinoria which comprise the cordilleran sector of the deformed belt trends northwesterly through the Digoel Mountains from the East Digoel River near latitude $5^{\circ}10'S$. It extends westward for at least 70 kilometers into the Maan-Tinne Highlands region of West Irian. A unique feature of this structure is its distinct eastward plunge. The anticlinorium is bounded on the north by the Juliana fault zone which also borders the southern margin of the Hindenburg anticlinorium. The southern margin of the Digoel anticlinorium is paralleled by a Pliocene basin and farther west beyond the Eilander East River, it is bounded also by the Sae fault-flexure zone.

In general these two westernmost structures seem to be associated with a greater degree of faulting than was their eastern counterparts, the Mueller anticlinorium. Indeed, van Bemmelen (1949, Fig. 377) depicted the gross structure of the central ranges of West Irian as that of an enormous horst. Bär et al. also agree that block

faulting predominated during the paroxysmal stage of orogenesis. Hence, it is possible that much of the anticlinal nature of the structures are due to flexing of the sedimentary cover over uplifted basement blocks. The Sae zone, which is developed as a flexure along the southeastern end of the Digoel anticlinorium, can be traced westward into a large zone of normal faulting.

In this respect it should also be noted that the Star Mountains have a very pronounced step-like structure (Fig.27), the steps being separated by the very strong fault-flexure zones. The top step is the metamorphic complex of the Boendermaker Range. The intermediate step consists of the Digoel and the westernmost part of the Hindenburg anticlinoria and is isolated from the adjacent steps by the Tahin fault zone on the north and the Sae fault-flexure zone on the south. It is capped by Mesozoic and Lower Tertiary rocks. The final, southernmost step is the Digoel synclinorium comprising Plio-Pleistocene rocks. This represents a total tectonic relief in excess of 8 kilometers.

Tahin and Om-Tari fault zone.-- The Tahin and Om-Tari fault zone, form the northern margin of the en échelon anticlinorial belt in the western cordilleran region. In general this fault zone separates the deformed Mesozoic and Tertiary rocks from the metamorphic-plutonic terrain to the north.

The Tahin fault zone was described by Bär (1961) in the Star Mountains region of West Irian. It has been traced from about lat 5°S.; long 141°E. along a west-northwesterly trend which nearly parallels the Sobger

I. STRUCTURE OF THE WESTERN CORDILLERA

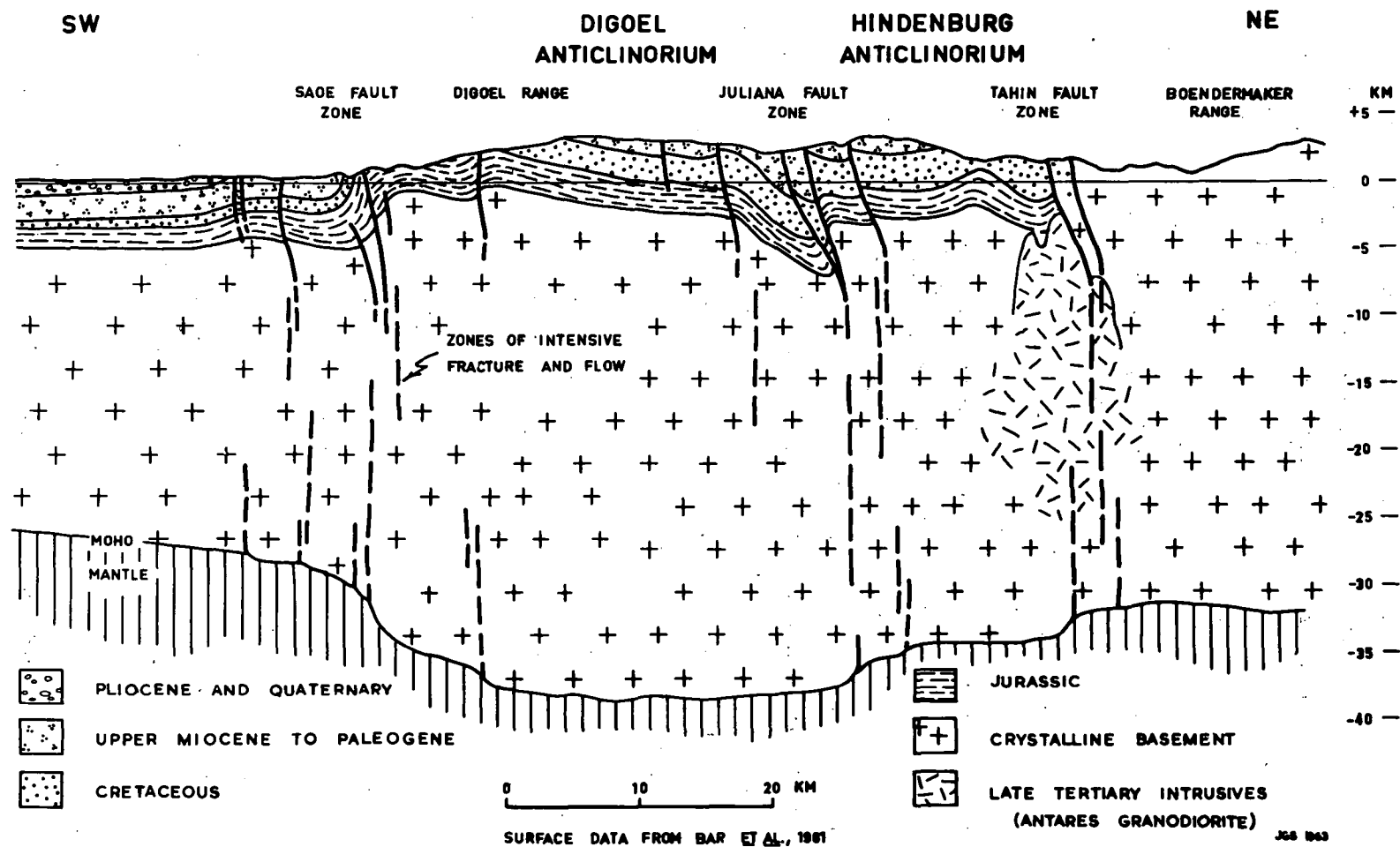


Figure 27

River to long 140°E . It is best known at the western end in the Ok Birim area where the fault zone is about one kilometer wide. The Tahin fault zone has been envisioned by Bär to have a steep (80°) northerly dip with the north side up. It places Cretaceous rocks with a west-northwesterly tectonic trend in juxtaposition with the so-called Boendermaker Metamorphics.

To the east the adjacent areas in the Territory of Papua and New Guinea have not been fully investigated, consequently it is not known if the Tahin fault zone actually extends into this region. However, in consideration of information shown on Plate 1 plus information obtained from investigations in the Upper Sepik region (S.J. Paterson, oral communication), I have tentatively extended the Tahin zone into the Territory of New Guinea and have connected it with the Om-Tari fault zone as shown on Figure 25.

The Om-Tari fault zone borders the northern flank of the Mueller Range anticlinorium. It emerges from beneath the volcanic mantle of Mount Rentoul near Tari, trends northwestward to the Om River, and continues into a zone of essentially no geologic information. From there I have extended it westward to connect with the Tahin zone. The Om-Tari zone is between 10-15 kilometers wide and involves successive slices of Upper Miocene and Lower Miocene rocks. Australasian Petroleum Company geologists (1961) have interpreted these faults as steep thrusts which flatten with depth.

Saoe fault zone.-- In a sense the Saoe fault zone is an integral part of the Digoel anticlinorium and has played

an important role in the development of that structure. Between the Eilanden East and the Kariem Rivers the Sae fault zone strikes west-northwest and in gross aspect is a great normal fault, although Bär et al. have mapped reverse faults in this zone. Eastward beyond the Kariem River the faulting is replaced by a flexure which plunges east-southeast beneath the Kau limestone in the Ok Ke-East Digoel area. Here Bär suggests the structure was eroded and presumably transgressed by the Kau limestones which would indicate that movement along the Sae zone had commenced in the Middle or Lower Miocene prior to the deposition of the Kau Limestone.

Juliana fault zone.-- South of the Tahin zone is a wide belt (35 kilometers) of longitudinal reverse faults which dip steeply to the north. These faults constitute the western extension of the so-called Hindenburg anticlinorium. The most conspicuous of the zones, the Juliana fault zone separates the westernmost end of the Hindenburg anticlinorium from the plunging end of the Digoel anticlinorium to the south. Bär notes considerable vertical displacements along these faults and suggests that the general geologic picture also indicates some lateral movement along the Juliana fault. They do not cite the evidence, however, nor the direction of movement, which would in any case be difficult to determine since the fault parallels the overall structural grain of the country. I do not refute the possibility of lateral movement along these faults and will consider this possibility in Section 2.5.2.

Although the Dutch workers have drawn this belt of faults to the International Border, the faults have never been recognized in Papua. This is probably due to one of three reasons. On the one hand geologic exploration in the region is just about nil. It is also possible that the faults have been eroded and have since been overlapped by Upper Miocene and Pliocene sediments in the Ok Tedi region. This is in accordance with the scheme proposed by Bär for the eastern end of Sae zone and would imply pre-Upper Miocene movement along this zone. A final and probably more likely explanation is that the faults die out into the Hindenburg anticlinorium.

It has been pointed out that the three main structural arches in the cordilleran sector of the fold belt are paralleled on the south by gently folded, nearly synclinal structural basins developed primarily in Pliocene and to some extent Upper Miocene rocks. From west to east they are referred to as the Digoel, Ok Tedi and Carrington basins. All are situated within the confines of the Pliocene Digoel-Strickland sedimentary basin.

Digoel basin.-- The Digoel basin lies in West Irian and is separated from the Digoel anticlinorium to the north by the Sae fault zone. Eastward in Papua it is joined by the Ok Tedi basin. Bär et al. (1961) report that

... the area is situated with gently tilted and slightly undulating strata (Plio-Pleistocene) at the surface. Some faults have been found here but they are of minor importance only. The general (tectonic) direction is parallel to that of the Central Range... It seems that the broad structure of the Digoel Mountain (Digoel anticlinorium) is slightly reflected in the Kau Limestones (Upper Miocene).

An andesitic neck is exposed through the Plio-Pleistocene rocks along the Kau River south of the Digoel Range (ca. lat $5^{\circ}30'S$.; long $140^{\circ}40'E$.).

Ok Tedi basin.-- The Ok Tedi basin parallels the southern edge of the Hindenburg anticlinorium. It is contiguous with the eastern end of the Digoel basin but the overall trend of the two basins is en échelon. Eastward the basin is overlapped by Pleistocene sediments in the Palmer River area. It is developed in gently folded Pliocene and Upper Miocene rocks in which several anticlines have been recognized: Muir, Tarim-Tedi, and Sadler's Nose. Again due to the lack of intensive geologic exploration these structures have not been described in great detail.

Carrington basin.-- The Carrington basin is an oval, synclinal basin developed in Pliocene and Upper Miocene rocks which border the southern margin of the Mueller Range anticlinorium. It lies northeastward and en échelon to the Ok Tedi basin. The basin trends northwest to southeast and the western end has a marked plunge to the southeast. To the southeast it disappears beneath the volcanic mantle of Mount Sisa and appears to have no extension beyond. The southwestern rim of the basin is formed by the Cecilia anticline beyond which the basin is overlapped by Pleistocene accumulations. In addition to the Cecilia structure several other anticlines are present in the basin including the Juhu, Pari, Asi and Pariania anticlines.

The Cecilia anticline (Fig.26) has been studied in detail by G.A.V. Stanley (JE, 1949). It is 70 kilometers

long and trends along the southern margin of the basin. It is interesting that although this is the first fold encountered in the deformed belt, it has a considerably larger amplitude than the associated folds closer to the orogenic center. G.A.V. Stanley has observed a fault along the southwestern side of the anticline which he interpreted as a thrust. It is possible that this fault may be of normal character and the Cecilia structure represents a fault-flexure zone much the same as the Sae zone of West Irian.

2.5.2 Origin of the Western Cordilleran Anticlinoria

Vertical movements.-- Superficially the structure of the western cordillera is very similar to that of the central cordillera. However, as I pointed out in the beginning of this section, there are apparently rather important differences in the tectogenic development of the two regions which in turn no doubt reflect basic differences in their original geosynclinal frameworks. I maintained earlier that the Kubor and Bismarck anticlinoria of the central cordilleran region were probably roughed out as early as the Mesozoic and certainly by the Lower Miocene. In other words these folds were developing as geanticlines throughout a large part of the diastrophic evolution of the central cordillera. Moreover, these geanticlinal massifs now form the core of the main mountain system.

The diastrophic development of the western cordillera did not follow this pattern. The western cordillera anticlinoria do not appear to have extensive crystalline cores which may be interpreted as former geanticlines nor

is there any indication that such geanticlinal highs existed at any time during the geosynclinal stages of diastrophism in the western cordilleran region. In fact the present anticlinoria developed entirely over the site of the earlier geosynclinal trough. Furthermore, the lithologic character of the rocks in the western cordillera seems to indicate that the Mesozoic and Tertiary development of the region was dominated by "stable" taphrogenesis characterized by a moderate but steady rate of subsidence and deposition typical of miogeosynclinal regions. This is in contrast to the more spasmodic, very mobile behavior of the central cordilleran region during the taphrogenic phases of diastrophism. Consequently, I suggest that the western cordilleran anticlinoria did not have a prolonged period of development dating back to the Mesozoic, but, instead, developed almost completely during the inversion or orogenic phase of diastrophism. The initial movements were perhaps as old as the Middle Miocene but the orogenic development did not begin in earnest until the Pliocene. This is partially suggested by the apparent lack of geanticlinal highs with which such early movements may have been associated. In addition, the nature of the limestones developed in the western cordilleran region during the Upper Miocene; i.e., shallow water reef-shoal limestones, suggests relative quiescence, whereas in comparable regions peripheral to the central cordilleran region, the Upper Miocene sediments are of a transitional environment and represent the initial phases in the development of a marginal exogeosynclinal trough. The Pliocene in the Digoel-Strickland exogeosynclinal basin, however, indicates that mountain-building movements were in action by that time in the western cordillera.

I must admit a certain amount of reservation in the foregoing statements in light of the exiguous nature of the information concerning these areas and the vast region which still remains to be investigated in the western cordillera. It may be possible that the metamorphics exposed in the Boendermaker Range were part of a geanticlinal system, similar to the Kubor-Bismarck complex, which has been strongly uplifted and stripped of its sedimentary veneer. Nevertheless the fact remains that the crystalline geanticlinal complex forms the heart of the central cordillera anticlinoria, whereas the Boendermaker metamorphic complex forms the northern flank of the western cordillera and as such were not so actively involved in the vertical movements associated with the Plio-Pleistocene phases of orogenesis.

Despite the apparent discrepancies in the historical development of the cordilleran regions the orogenic mechanisms were basically very similar. I suggest that the western cordilleran anticlinoria were also formed primarily by differential vertical movements of the crust. These movements are of the same type described for the central cordillera and took place along a series of zones of flow and/or fracture which separated the cordilleran crust into great elongate blocks. This type of movement is particularly well expressed by the step-like structure developed in the Star Mountains region. In the eastern parts of the Hindenburg and Mueller anticlinoria the faults which define the basement blocks are not reflected at the surface and in general the structure is less complicated with only minor folds developed on the anticlinoria. This probably means that the flow by which the uplift was accomplished was uniform across the anticlinoria and flow lines did not bunch together to

form faults.

The Om-Tari fault zone, which bounds the north-eastern margin of the Mueller anticlinorium, poses a difficult problem. Referring to Figures 25 and 26 it can be seen that this zone in many respects strongly resembles the Kutubu- Sireru imbricate belt. There are two possible mechanisms by which this fault zone may have originated. In the first place, if it does in fact connect with the Tahin fault zone as has been suggested, then it may be explained as a series of splays off the main Tahin zone. In this respect it would be very similar to the pattern of the Bismarck fault zone and probably related to transcurrent movements at depth beneath the western cordillera. This is the alternative which I prefer. However, it may be also considered as a western extension of the Kutubu- Sireru imbricate belt and as such be due to tectonic transport by gliding off the rising central cordillera. As can be seen on Plate 1 the imbricate belt parallels the axis of the central cordilleran uplift and, thus, this latter suggestion may be regarded as a possible solution.

Horizontal movements.-- It has already been demonstrated that the tectonic pattern of the central cordilleran region strongly suggests that horizontal movements between fault-defined crustal blocks have played an important role in the overall diastrophic evolution of the orogen. Very similar structural patterns are developed in the western cordillera which indicate that strong horizontal movements have been superimposed on the vertical movements. Specifically, this movement is evidenced by the en échelon and sigmoidal outlines of the three main anticlinoria and the associated fault zones (Fig.25).

Again the zone of maximum strain trends east-west to west-northwesterly across the region and the resulting rotations are in the sinistral sense. The strain was probably concentrated along the major fault zones separating the basement blocks. As was the case in the central cordillera the east-west trending segments of these faults would be expected to exhibit the largest element of sinistral strike-slip motion while the northwesterly trending segments would be likely to have a considerable dip slip component of movement related to compressional stress directions of simple shear. It must again be emphasized that the compressional deformation associated with this transcurrent movement is not the primary tectonic agent in promoting the tectonic relief of the region. The fundamental mechanism controlling the primary vertical movements within the orogenic zone will be considered in the subsequent chapters.

3. ROLE OF HORIZONTAL MOVEMENTS IN THE DIASTROPHIC EVOLUTION OF WESTERN PAPUA AND NEW GUINEA

The previous sections have been devoted to the study of the superstructure of the New Guinea orogen. I have examined the configuration and the historical development of the Papuan geosynclinal system, as well as the folding and faulting that were superimposed on the geosynclinal regime primarily as a consequence of vertical movements which accompanied the inversion of the geosyncline or the upheaval of the orogen.

The problem now at hand is to examine the nature and origin of the fundamental framework or infrastructure of the orogen. Careful consideration of the diastrophic framework of New Guinea suggests that this framework has developed almost entirely as a response to horizontal movements of the earth's crust. Furthermore, the character of this horizontal movement is quite complex and appears to represent a hierarchy of several superimposed kinematic modes. It is thought that these modes of movement can be differentiated into two modes of deformation: extension and simple shear; and two of displacement: translation and rotation.

It is my contention that extension deformation is the foremost element in this hierarchy of horizontal movement and is the primary process in the formation of

geosyncline and ocean basins. The structural complexity typical of most orogenic belts is introduced by the superposition of simple shear, translation and rotation upon the basic extension framework. These movements have a profound effect on the development and configuration of the geosynclinal belts and the subsequent orogen.

In the following sections I propose to develop independently the evidence for each of these types of horizontal movement that are present entirely within the realms of western Papua and New Guinea. Finally, I will show how all these movements are substantiated by several lines of deductive reasoning and, furthermore, how they can be integrated into a completely consistent, general pattern of deformation. The age and magnitude of these movements will also be considered.

In a later section I will point out in a broader context the profound implications of these horizontal movements in the diastrophic evolution of the entire Australasian region.

3.1 EXTENSION HYPOTHESIS OF TAPHROGENESIS

The following section is concerned with the processes of geosyncline formation or taphrogenesis. There are, perhaps, as many hypotheses for the origin of geosynclines as there are geosynclines, probably more. Among these, many have completely lost favor with contemporary geologists, and agreement as to the acceptability of the remainder is still in a state of flux. Unfortunately the ultimate, universally accepted hypothesis does not appear to be imminent. It is certainly beyond my design to review all these hypotheses as to their possible application to the Papuan geosynclinal system. Nor am I able to make any radical contribution to the general understanding of geosynclinal processes. Rather, it is my intention to develop in some detail, and often in a somewhat modified form, the hypotheses or combinations of hypotheses which I feel are the most compatible with our present knowledge of the nature of the Papuan geosynclinal system.

Careful consideration of the morphology and diastrophic evolution of the Papuan geosynclinal system and the available geophysical information has led me to the conclusion that this geosyncline can be adequately represented by a model based on the extension hypothesis of geosyncline formation. The characteristics of the Papuan geosynclinal system which support this conclusion

will be examined in Section 3.1.2 after a brief review of the fundamental tenets of the extension hypotheses.

Extensional rifting and stretching of the earth's crust is certainly not a new concept in geotectonics and for many years it has been considered in one form or another to be a possible solution to the problem of geosyncline formation. As long ago as 1908, Lukashevitch in Russia had propounded a tensional origin for geosynclines. Bucher (1933) was also an early proponent of the tensional or stretching origin of geosynclinal zones. Bucher and also Cloos (1948) arrived at this conclusion through their studies of major tectonic lineaments associated with geosynclinal regions. In a similar light Ver Wiebe (1936) concluded that geosynclines were controlled by great zones of fracturing which he called geosynclinal boundary faults. In more recent years detailed stratigraphic and structural work in the major orogenic zones throughout the world has increasingly demonstrated the importance of tensional processes in the geosynclinal phase of diastrophism.

For example, Trümpy (1960) has pointed out that normal faults and flexures, probably related to tensional stresses in the crust, formed the margins of the Mesozoic pre-orogenic troughs in the Alps. There is also considerable evidence of the tensional development of the marginal geosynclines flanking the Atlantic and Gulf coasts of the United States.

3.1.1 Mechanisms of Crustal Extension

At present there are two hypothetical geotectonic mechanisms which could adequately explain the formation of geosynclines by rifting and stretching associated with

extension of the lithosphere. These are: (1) subcrustal flow in response to some physical or chemical gradient within the mantle, and (2) the expansion of the earth. In the following pages these basic mechanisms will be briefly reviewed and examined in regard to their potential as a factor in the development of the Papuan geosynclinal system.

Subcrustal flow.-- Subcrustal flow due to physical or chemical gradients within the mantle has long been considered as a very important diastrophic mechanism. In this discussion I will deal particularly with convection currents which are attributed to thermal gradients within the earth. However, by doing this I am not denying the possible existence of other types of subcrustal flow that for instance is proposed by van Bemmelen (1954) and many others. Many of the conclusions made here will in general hold true for any type of subcrustal flow.

The concept of convection currents was developed as a diastrophic mechanism applicable to the East Indian region by F.A.Vening Meinesz (1934). In his opinion geosynclinal troughs and subsequently orogenic belts developed over zones where the crust had been drawn downward by descending convection currents. The "plastic-buckling" or "tectogene" hypothesis was further developed and modified by Kuenen (1936), Hess (1938) and Griggs (1939). This buckling process was thought to cause a considerable thickening beneath deep sea troughs and geosynclinal zones.

However, the crustal studies, which have been made recently by Worzel and Shurbet (1955) in the Puerto Rico region, indicate that the crustal thickness beneath ocean

deeps is reduced rather than thickened as Vening Meinesz and others have thought. Consequently, Worzel and Shurbet are in favor of a tensional origin for the trenches. Hence, it appears likely that if convection currents play a major role in the formation of ocean deeps or geosynclines, it is most likely to be in a manner opposite to the original and commonly accepted view; i.e., geosynclines would form above rising divergent currents which would tend to thin the crust by stretching and rifting. However, there is some possibility that the convergent, downward directed flow might cause thinning of the crust by some process of subcrustal "erosion" as mentioned by Gilluly (1955). In such a process material would be "plucked" from the bottom of the crust by the descending convection currents. Nevertheless, ascending and divergent flow is thought to be the best configuration for the production of crustal stretching in the geosynclinal belts.

Kraus (1951;1959, Fig.31) has depicted the present structure of the great Meervlakte-Markham depression to be an extensional structure related to "bathyreal" underflow. Rade (1954) has proposed a somewhat modified version of Kraus's pattern to account for the apparent southerly or southeasterly movement of the crustal blocks lying north of the Ramu and Markham rivers (Adelbert, Finisterre and Saruwaged Mountains) relative to the main New Guinea mass to the southwest. This latter analysis is important in that it draws attention to the possibility of major transverse movements within New Guinea. My analysis indicates that such movements are certain to have played a major role in the deformation of the Papuan geosynclinal system

and consequently must be explained by the basic diastrophic mechanism, which in this particular case is subcrustal currents. However, it is quite possible that subcrustal flow can be manifested in the crust as both transcurrent movement and extension in a fashion very similar to that suggested by Carey (1958) and later by Hamilton (1961) for the origin of the Gulf of California.

This section, however, is limited to the processes of extension and the evidence for such deformation within the Papuan geosynclinal system.

Expansion of the earth.-- Egyed (1957), Carey (1958), and Heezen (1960) have maintained that the general expansion of the earth is the fundamental diastrophic mechanism and, consequently, all the features of the earth's crust are intimately related to this process. Egyed suggested that this expansion was manifested in the upper layers of the crust as deep fractures and also graben structures including geosynclines. He stated that, "The long, striking basins of the geosynclines suggest that in the geosynclinal area the thickness of the tectonosphere (crust) is reduced greatly by a stress pattern brought about by expansion."

Carey (1958) has outlined in some detail the mechanic processes by which crustal rifting and stretching could occur in response to an expanding earth. He emphasizes that while crustal extension would in most cases be expressed at the surface by tensile fracture, at depth this deformation passes into brittle shear, ductile shear and finally into flow. At any one level of the crust the nature of the deformation is controlled to a large extent by the rate of extension. If for instance

the extension is slow, it is most likely that the deformation would be by flow. However, if the rate of extension is rapid and the stress exceeds the shear strength and finally the tensile strength of the crust, failure by fracture results.

In addition to this variation in mode of deformation with changes in the rate of extension, there is also a corresponding variation with depth. At the surface and in the upper layers of the crust physical conditions, particularly temperature and confining pressures, are such that the tensile strength of the crust is easily overcome by extension giving rise to graben and "basin and range" structures. However, at greater depths with correspondingly greater temperature and confining pressure and lower viscosity, deformation will occur by shear and by plastic flow. This point is emphasized by Kanizay (1962). Hence, according to the extension hypothesis of graben and geosyncline formation, the upper layers of the crust are generally faulted while the lower layers are stretched. The well known clay models produced by H.Cloos (1939) provide an ideal graphic representation of these developments which are illustrated in my sections drawn through the Papuan geosynclinal system (Plates 6 to 9).

Carey further emphasizes that this stretching may develop to such an extent that the simatic layers of the crust and perhaps even the mantle are exposed. Both Carey and Heezen consider the oceans to be formed by this mechanism, thus giving rise to continental drift or separation.

Carey has strongly maintained that such crustal rifting has played a major role in the development of

the southwest Pacific region. This is strongly suggested by the "detached" continental blocks of New Guinea, Solomons, New Hebrides, Fiji, New Zealand and others. All these fragments are separated from the main Australian block by oceanic crust (e.g., Tasman sea; Officer, 1955), which eliminates the possibility that the apparent detachment resulted through "foundering" of continental crust. In addition the tremendous thickness of sediments which accumulated in both the New Guinea and New Zealand geosynclinal troughs would seem to demand a far greater source than is now apparent.

3.1.2 Origin of the Papuan Geosynclinal System

In the light of the preceding discussion it should be possible to examine by deductive methods the validity of the extension hypothesis of taphrogenesis as it may be applied to the Papuan geosynclinal system. If the geosynclines did originate due to these tensional processes, then this development should be reflected in the morphology of the geosynclinal troughs, the nature of the geosynclinal sediments, and finally to some extent in the present crustal structure. These are the features which will be examined in the following pages.

Southern geosynclinal margin.-- It was stated in Section 1.7.4 that during the Mesozoic a geosynclinal trough of considerable dimension, (Kutubu trough, Fig.17) cut across Papua from the Star Mountains region southeastward to the Delta embayment region and probably farther. The Kutubu trough represented the initial stages in the fragmentation of the anorogenic Papuan platform, and it is very likely that the southwestern or external margin of this trough was defined by and developed along a series of geosynclinal boundary faults.

The Komewu fault (Section 1.7.2; Figs. 14 and 15) is positive evidence of geosynclinal boundary faulting. I interpret it to reflect the general extensional stress regime which dominated the development of the southwest margin of the Kutubu trough from its inception in the Jurassic until its degeneration in the Paleogene. The magnitude (ca. 1200 meters stratigraphic offset) of this fault system, which is thought to have developed in the late Cretaceous or Paleogene, indicates that the extensional stress was considerable even at a stage when the tendency of the trough was toward that of stabilization.

During the Jurassic and early Cretaceous, when geosynclinal sinking was at a maximum, these tensional rifting movements would have been much stronger. Such activity is witnessed by the character of the basal Jurassic conglomerates (Section 1.7.3) developed in the Wok Feneng areas of the western cordillera. These deposits, which are 280 meters thick, consist of conglomerates and sandstones containing angular cobbles and boulders of coarse pink granite. It is suggested that these materials were derived from the pre-Jurassic crystalline basement exposed in fault scarps and flexure zones forming the southwestern, external margin of the Kutubu trough. Conglomerate units between 55 and 250 meters in thickness are also associated with the sandstone sequence comprising the early Cretaceous of the Star Mountains region of the western cordillera. These rocks probably have a similar origin and are probably related to early Cretaceous phase of marginal geosynclinal faulting.

Northern geosynclinal margin.-- Until now this study had been concentrated on the central cordillera of

western New Guinea and Papua and the foothills region to the south. However, it is now necessary to examine briefly the northern ranges of New Guinea for information which will aid in a more comprehensive understanding of the basic framework of the Papuan geosynclinal system and the nature of its northern margin with particular reference to the Mesozoic development.

As yet no fossiliferous Mesozoic rocks have been recognized anywhere in the northern ranges. In the Bewani, Torricelli and Prince Alexander Mountains the very thick accumulations of Miocene and younger Tertiary rocks rest directly on crystalline basement rocks. Similarly the thick Tertiary strata in the Adelbert, Finisterre and Saruwaged Mountains are thought to rest on crystalline basement. Hence, it is tentatively suggested that this region, which will be called the northern massif, was emergent throughout the Mesozoic or at least in the latest Mesozoic and formed the northern margin of the Mesozoic Papuan geosynclinal system.

It is quite likely that the crystalline rocks in the cores of these mountains were also part of the original anorogenic quasi-craton which was fragmented, beginning in the Triassic, to form the Papuan geosynclinal complex. In detail the northern massif may have consisted of a contiguous series of geanticlinal highs which were similar to the Kubor and Bismarck massifs.

There are two main features of the Mesozoic Papuan geosyncline which suggest that its northern border, which probably coincides rather closely with the present Sepik-Ramu-Markham depressions, may have been controlled by very important faulting. In the first

place the zones of maximum accumulation of Mesozoic strata; viz., the Wahgi and Ramu trough complex, lay in the northern third of the mobile belt giving the geosyncline a pronounced north-facing asymmetry. Finally, without exception the initial or ophiolitic magmatism which accompanied the development of the intrageosynclinal troughs was also restricted to the northern margins of the geosynclinal complex. This indicates that these fluids were migrating upwards and into surficial layers of the crust along some important zone of weakness. Both these relationships; i.e., the asymmetry of the geosyncline and the localization of the ophiolitic magmas, would be compatible with the notion that the northern margins of the Mesozoic geosynclinal system was controlled by deep fractures formed as the result of extension of the earth's crust.

Beginning in the lower Tertiary the character of the northern massif was reversed and it became the site of considerable geosynclinal sinking which, of course, had the effect of considerably altering the northern margin of the Papuan geosynclinal system. These later movements in the northern ranges are beyond the scope of this study. It is most important here to learn the configuration of the Mesozoic geosynclinal system which most likely formed the basic framework for later developments.

Kubor and Bismarck massifs.-- There is very little information available concerning the nature of the internal margins of the Papuan geosyncline; i.e., the margins of the Kubor and Bismarck massifs. I have previously (Sections 1.9 and 2.2.2) presented evidence which suggests that these crystalline massifs were positive areas throughout the Mesozoic. I suggest that these blocks may repre-

sent horst-like remnants of the original Papuan crystalline platform which became separated from adjacent parts of the platform due to the anastomosing character of the fracture systems which defined the geosynclinal troughs during the early stages of their growth.

The horst-like nature of the Kubor and Bismarck massifs continued during the Lower Miocene. This notion is again mainly substantiated by the coarse nature of the sediments which flank these massifs, particularly the basal "e" stage conglomerates which occur on the southern flanks of the Bismarck high (Section 1.5.2, Fig.10).

Furthermore, the thickness gradients of sedimentary accumulations developed around these blocks are such that they would seem to imply subsidence of the geosynclinal troughs along a series of steep and often very large faults.

Finally, the high incidence of ophiolitic magmatism particularly along the Bismarck trend indicates that the crust was here, as along the northern geosynclinal margin, fractured to such an extent that these magmas and other fluids could pass easily into the upper layers of the crust and to the surface. Such fracturing and accompanying magmatism would be at a maximum in the presence of a tensional stress regime as emphasized by Rittmann (1962).

Erave-Wana swell.-- The Lower and Middle Miocene Erave-Wana swell also has certain horst-like characteristics. This is particularly true of its northern border which separates it from the Kaugel trough in the Pio-Purari region. Quite thick Lower and Middle Miocene graywackes are developed immediately adjacent to the northern margin

of the swell. Considerable thicknesses of conglomerate containing clasts up to 1.6 meters in diameter (Pio conglomerates) are associated with these rocks. There is, also, a great deal of slumping developed within the graywacke-conglomerate sequence and these facts suggest that deposition was on or adjacent to a steep, highly mobile slope or series of scarps that were actively controlled by faulting. Kent and Rickwood (LW, 1956) have suggested that the Hui fault which parallels the northern margin of the swell may have been active at that time.

3.1.3 Pattern of Geosynclinal Rifting

The next few pages will be largely devoted to several comments concerning the pattern of geosynclinal rifting and its implications on the nature of forces producing this movement. The discussion will be somewhat restricted at this point since it is quite likely that simple shear deformation, translation and even rotation may have to some extent all played a role in the taphrogenic development of the orogen. Nevertheless, it is worthwhile to consider the extension independently, since, for reasons I will discuss later, it is likely to be the most basic process in the formation of the Papuan geosynclinal system.

As I have mentioned on several occasions, the Papuan geosynclinal system is thought to have developed by means of fragmentation of a rather extensive platform terrain. This platform, which consists for the most part of metamorphic and plutonic rocks, was the result of a phase of cratonization which terminated a pre-Mesozoic cycle of diastrophism.

Fragmentation or geosynclinal rifting of this platform began in the Triassic as evidenced by the Triassic graywackes, arkoses and associated sediments in the western Bismarck Range. Unfortunately, the information concerning these rocks is quite restricted and it is impossible to infer the original extent of the Triassic rift system and, accordingly, the stress system producing extension.

Geosynclinal rifting and stretching was quite active during the Jurassic and early Cretaceous and gave rise to an extensive geosynclinal terrain (Fig.17). From this figure it is quite apparent that rifting was occurring in several zones which were partially separated by horst-like geanticlines. Certainly during the Jurassic rifting had developed to an extent where the Kubor geanticline had become isolated and was bordered on the south by the Kutubu trough and on the north by the Wahgi trough. It is not certain, however, whether or not the Bismarck block had by this stage become isolated along its northern margin.

Some idea of the orientation of the extensional stresses can be obtained by the examination of the pattern of the Mesozoic geosynclinal system. It has been shown that the southern boundary of the geosyncline is rather well defined. In West Irian it trends east and then swings southeastward at the Papuan border to strike the Gulf of Papua near the mouth of the Kikori River. The northern margin of the Mesozoic mobile belt is thought to have coincided with the present Sepik and Ramu depressions. Figure 28 illustrates this pattern of geosynclinal development and the corresponding directions of maximum extension.

In applying these strain directions to the geosynclines I have assumed that the direction of maximum

MESOZOIC GEOSYNCLINAL FRAMEWORK

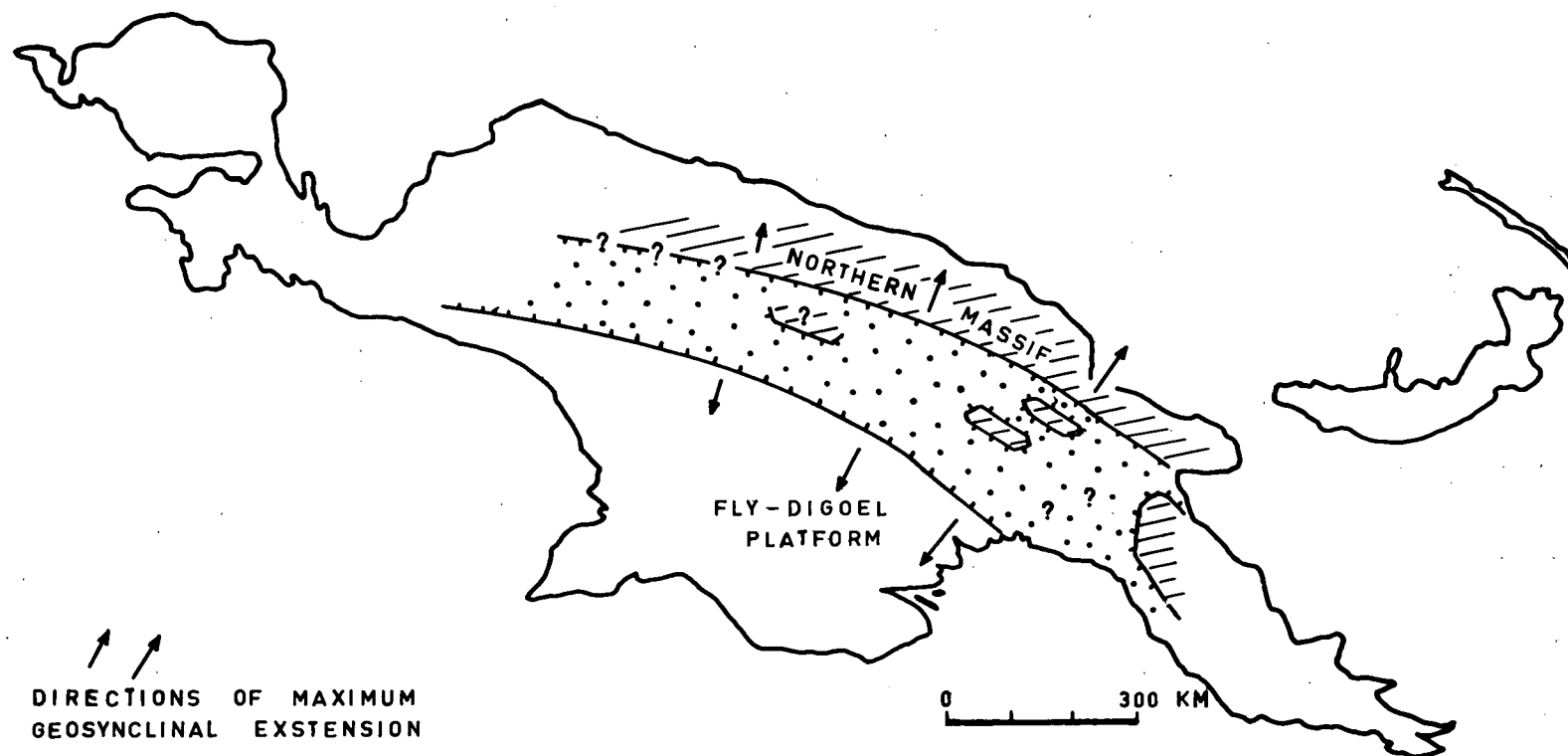


Figure 28

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extension is perpendicular to the strike of the fault-controlled geosynclinal margins. Similar patterns of tensional rifting have been produced in model experiments by E.Cloos (1955) and more recently by Oertel (1962). It is my contention that this type of strain pattern is a reasonable approximation of the conditions which dominated the development of the Mesozoic Papuan geosynclinal system and in turn served as a framework for the subsequent Tertiary phases of taphrogenesis.

Thus it can be seen that the extensional stresses that gave rise to the geosynclinal rifting and stretching lay in a generally northerly direction. These stresses were most likely to have been generated either by a zone of rising and divergent subcrustal flow which lay beneath the axis of the geosyncline or due to general extension related to the expansion of the earth.

However, it must be remembered that the pattern of folding developed in the central and western cordilleran regions suggests a strong element of simple shear in the total deformation of the orogen. The potential role of this simple shear deformation during the geosynclinal phases of diastrophism will be examined in a following section.

3.1.4 Thickness of Subgeosynclinal Crust

If the Papuan geosynclinal system developed in response to extensional stresses in the earth's crust then it is to be expected that the crust beneath the geosynclinal troughs would be considerably thinned. Furthermore, if such thinning does in fact occur, it would have an important effect on the magmatic and the subsequent orogenic development of the mobile belt. Consequent-

ly, it is appropriate to make some approximation of the configuration of the crust beneath the geosynclinal system. In general structural cross sections, which show the configuration of the subgeosynclinal crust including the Mohorovicic discontinuity, facilitate deeper understanding of the basic processes of diastrophism and are all too often omitted in geotectonics studies.

To construct such sections it is necessary to make a series of rather fundamental assumptions which, however, are justified by the results. In the first place it is necessary to assume that the geosynclinal troughs developed in an approximate state of isostatic equilibrium. This is not an unreasonable assumption since it has been shown in the case of the post-glacial uplift of Fennoscandia (Gutenberg, 1941) that quite large isostatic anomalies which are distributed over areas equivalent to the size of a geosynclinal belt can be at least half corrected in a period of about 10,000 years which represents a small increment in the total development of a geosynclinal belt; e.g., at least 200 million years in the case of the Papuan geosynclinal system. The greater rate of deformation in geosynclinal regions is balanced by the lower viscosities associated with higher temperatures and isostasy is still maintained in the long run.

On this basis some approximation of the crustal structure beneath the Papuan geosynclinal system can be worked out according to the following relationship based on the Airy hypothesis of isostasy in which all crustal columns have the same weight. Furthermore, an original or "standard" crustal thickness of 33 kilometers (Worzel and Shurbet, 1955) and a density of 2.84 is assumed. The relationship, which has been used by Hsu (1958), is as

follows:

$$T_c \rho_c = T_s \rho_s + T'_c \rho_c + T_m \rho_m + T_w \rho_w$$

Where:

T_c = Thickness of crustal blocks with tops at sea level
= 33 kilometers = depth of compensation

T'_c = Thickness of the crustal blocks under the geosynclinal troughs

T_s = Thickness of sedimentary accumulations

T_m = Thickness of the mantle which compensates for the deficiency in mass of the sedimentary accumulations
= $T_c - T'_c - T_s - T_w$

T_w = Thickness of water

ρ_s = Density of sedimentary accumulations in the Papuan geosynclinal system (gm/cc)

(2.5) Volcanogenic accumulations (Wahgi and Ramu troughs)

(2.3) Omati, Kaugel, Kutubu troughs and Fly-Digoel platform

ρ_c = Density of crust (2.84)

ρ_m = Density of mantle (3.27)

ρ_w = Density of water (1.03)

Hence:

$$T'_c = \frac{T_s \rho_s - T_c \rho_c + T_w \rho_w + \rho_m (T_c - T_s - T_w)}{\rho_m - \rho_c}$$

Since we already have some knowledge of the thickness and nature of sediments and consequently the morphology of the geosyncline, it is possible to solve the above equation for the thickness of the subgeosynclinal crust. The relationship of T'_c and T_s for densities $\rho_s = 2.3$ and $\rho_s = 2.5$ is shown in Figure 29. For instance the thickness of the volcanogenic sedimentary

accumulations (2.5) which accumulated in the Wahgi trough by the end of the Lower Miocene is at least 12 kilometers thick and possibly as great as 17 kilometers. According to Figure 29 the crustal thickness beneath the Wahgi trough would be reduced to 11.5 kilometers. If 19 kilometers of sediments with a density of 2.5 would have accumulated in the trough, they would have to rest directly on mantle material to be in isostatic equilibrium. If the sediments were less dense or the original (pre-rifting) crust was thinner, then the mantle would rise correspondingly higher under the geosynclinal troughs. The gravitational effect of water, the depth of which probably in no case exceeded 1000 meters, has been disregarded to ease the construction of the cross-sections. Figure 30 and the geosynclinal profiles in Section 4.5 (Plates 6 to 9) were constructed by this method.

Assuming the validity of these constructions it is possible to make a crude approximation of the amount of Mesozoic and Tertiary geosynclinal extension. Since in any one profile the area of the crust presumably has remained constant throughout rifting and stretching, it is possible to compute the original width of the cratonic platform from which the Papuan geosynclinal system developed. The schematic profile in Figure 30 is 250 kilometers long and the cross-sectional area of the crust is 5600 km^2 . Since the crust was assumed to have had an originally uniform thickness of 33 kilometers, it follows that the original distance AB would have been 170 kilometers. Thus the Papuan geosynclinal belt may have expanded some 80 kilometers or 46 percent between its inception in the Jurassic and the Lower Miocene.

THICKNESS RELATIONS OF CRUST AND
SEDIMENTS IN AN ISOSTATICALLY
ADJUSTED GEOSYNCLINAL SYSTEM

$$T_c' = \frac{T_s \rho_s - T_c \rho_c + \rho_m (T_c - T_s)}{\rho_m - \rho_c}$$

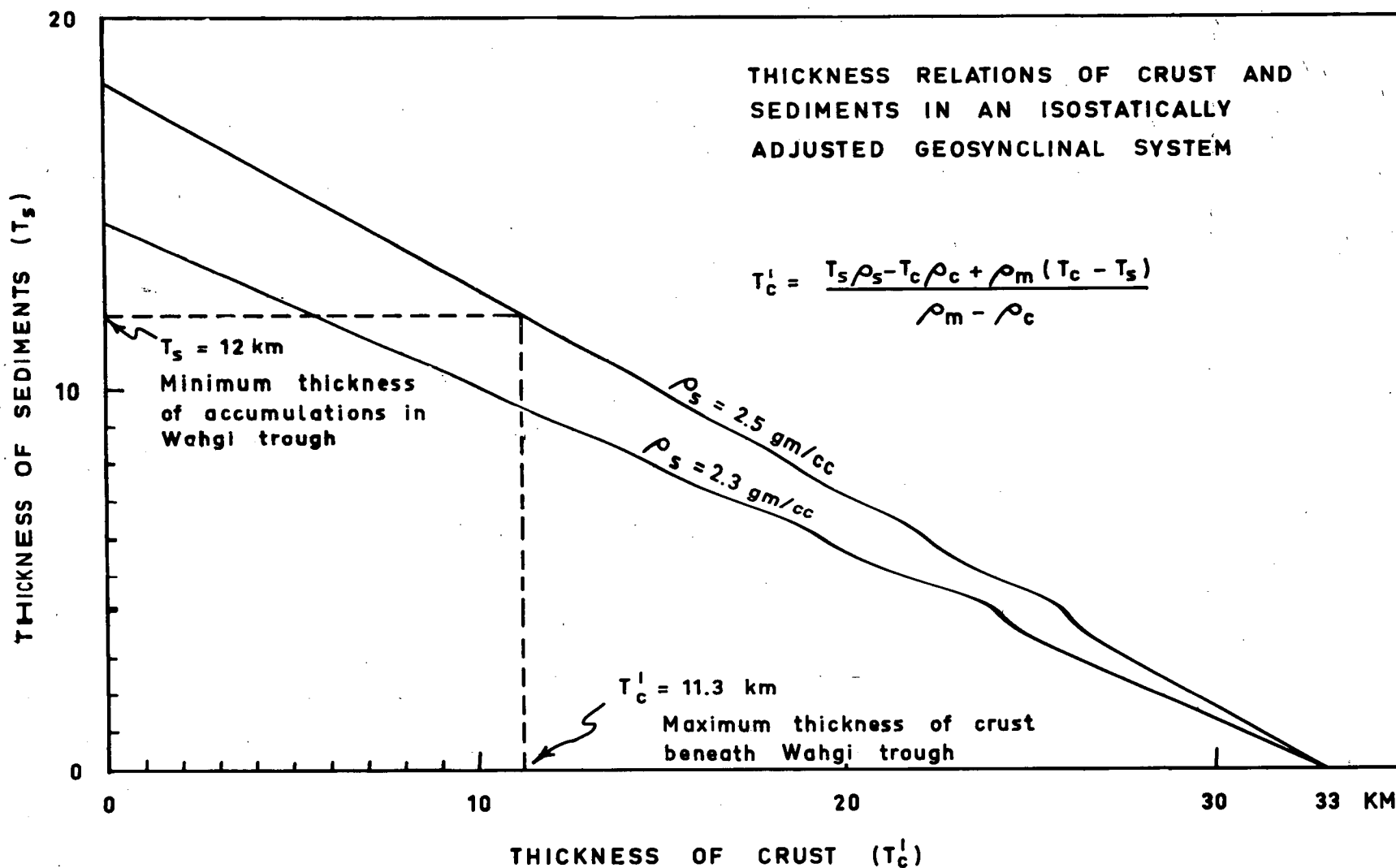
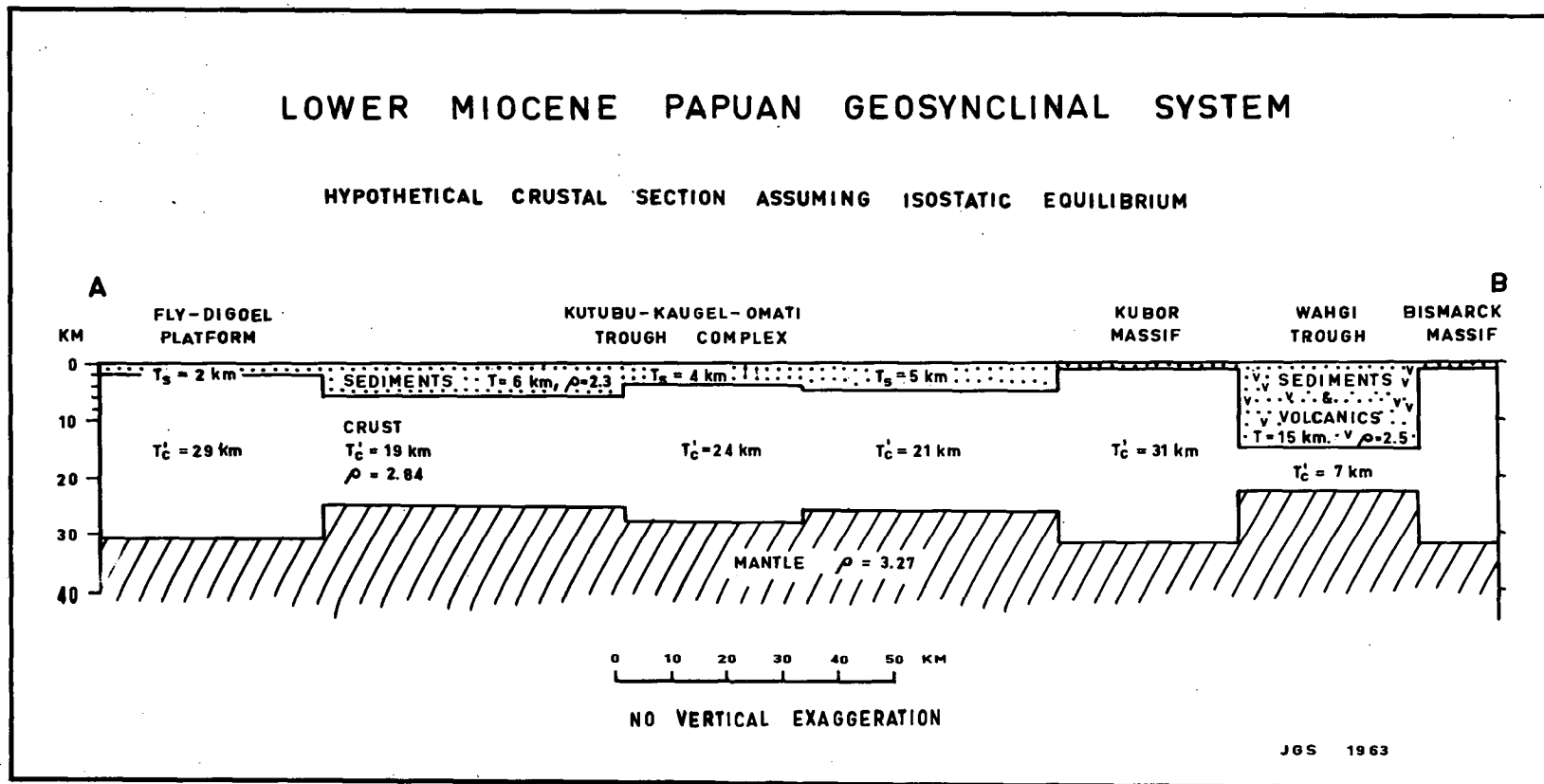


Figure 29

Figure 30



3.2 SIMPLE SHEAR DEFORMATION AND TRANSLATION

In the previous section I suggested that the development of the Papuan geosynclinal system was to a large extent attributed to an extensional stress system oriented perpendicular to the geosynclinal trend. However, the complexity of the patterns of folding and faulting in New Guinea makes it apparent that other types of deformation have certainly played a decisive role in the orogenic stages of diastrophism and quite likely they have also been active in the taphrogenic development of the region. Into this category of movement falls simple shear deformation, translation and rotation, all of which operate in a horizontal plane.

The following pages are devoted to a study of the horizontal movements commonly called wrench-fault or transcurrent tectonics and their application to the orogenic belt of western Papua and New Guinea. Wrench-fault tectonics have played a fundamental and continuous role in the development of circum-Pacific orogenic belts. Important movements of this kind have been described along the San Andreas fault in California as well as in Chile, Japan, Philippines, Taiwan and New Zealand. Recent first motion studies of earthquakes in the Pacific (Ritsema and Veldkemp, 1960; Balakina, 1962) have also verified the importance of lateral movements in which the null axis or intermediate stress axis is vertical. Con-

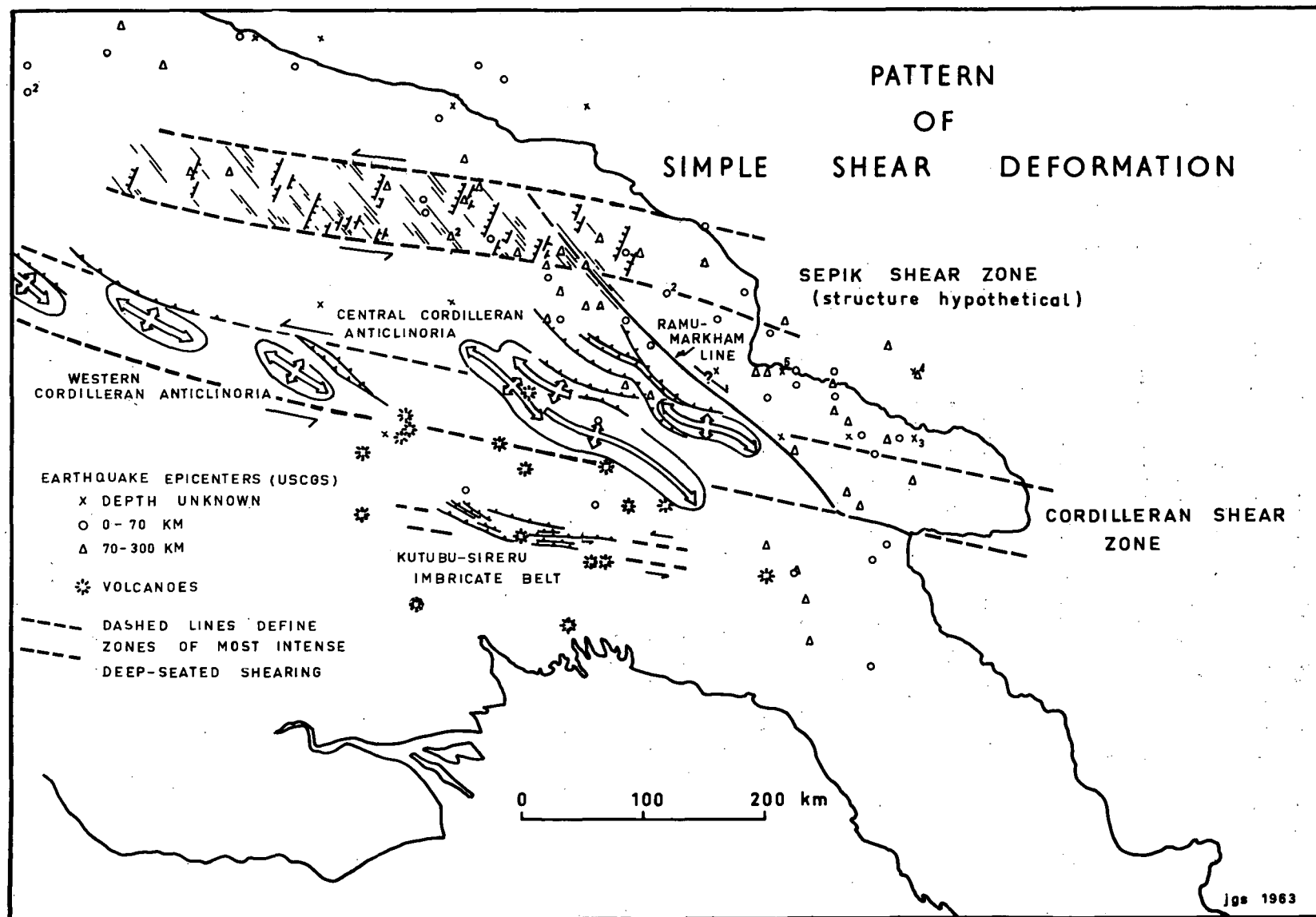
sequently, it would be logical to expect that transcurrent movements have also played an important role in the diastrophic evolution of New Guinea. Furthermore, at a global scale, if one accepts either the concepts put forward by Carey (1958) for a gross shift of the southern hemisphere eastward relative to the northern hemisphere or Jardetsky's (1962) concepts of zonal rotation of the earth, it can be seen that New Guinea, which lies in the critical equatorial zone, should experience considerable lateral deformation and displacement.

3.2.1 Cordilleran Shear Zone

Deep-seated, lateral movements appear to be expressed in several important structural zones within the New Guinea orogen (Fig.31). One of the most interesting of these has here been called the cordilleran shear zone. As the name implies, the cordilleran shear zone in general coincides with the crest and sometimes the southern margin of the main cordillera in a linear belt which extends westward from the headwaters region of the Ramu and Markham Rivers at least 600 kilometers into the Star Mountains region of West Irian. The zone is in the order of 50 kilometers in width and embraces both the central and western cordilleran anticlinoria. In fact, this zone has been postulated mainly on the evidence of strong simple shear deformation exhibited by the patterns of folding in both the western and central cordilleran regions (Sections 2.2.2 and 2.5.2; Figs. 20 and 25).

In this respect it can be seen that this zone of lateral movement is quite different from the types of transcurrent zones commonly described in the literature. In the well known transcurrent zones; e.g. the San Andreas fault, a large part of the shearing strain is relieved

Figure 31



along a relatively discrete fault zone. However, it is just as likely, perhaps more so, that deep-seated lateral movements would manifest themselves at the surface as a broad zone of en échelon and sigmoidal folding and faulting rather than as a discrete fault line. This is especially true of young geosynclinal systems such as in New Guinea in which the strains generated at depth are propagated upward through a thick pile of plastic sediments which are far more likely to yield by flow (folding) than by fracture even at relatively high rates of stress application. Even in zones where the movement is for a large part relieved along a discrete line, there are systems of en échelon folds and faults associated with the main trend which indicate that the strain resulting from lateral movement at depth is spread across a rather wide belt. I have recognized other zones of lateral movement of this type (ms. in preparation) in the northwestern United States, and it is likely that the careful study of tectonic patterns in other major orogenic belts in terms of simple shear deformation will indicate that considerable lateral movement at depth has played an important role in the tectonic development of these areas.

3.2.2 Purari Shear Zone

In addition to the cordilleran zone, there are several other zones of lateral movement which roughly parallel the New Guinea orogen. One of these is the Purari River zone. In Section 2.3.2 I cited the evidence for an important element of sinistral transcurrent movement along the Purari fault which is founded mainly on the en échelon patterns of anticlines intimately associated with the fault in much the same fashion as the New Port-Inglewood belt in Southern California is related to the

San Andreas fault (Reed and Hollister, 1936). It is thought that the Purari fault is only one in a series of faults in the foreland belt which may have a considerable component of lateral movement. Here, I refer to the linear zone of steep faults which I described as the so-called Kutubu-Sireru imbricate belt in Section 2.3.1. The faults, which form a zone 200 kilometers long by 20 kilometers wide, have several morphological characteristics of transcurrent faults. In particular they have very steep dips and linear, continuous trends (up to 100 kilometers in length) which cut through the regions of high relief with little or no deflection. However, these faults are not primarily of a transverse nature but have originated with the foreland folding complementary to the uplift of the central cordillera. The sinistral transcurrent movements originate beneath the décollement which forms the base of the folded sequence but, nevertheless, are propagated upward into the folded sheet and are likely to be expressed along the steeply dipping Kutubu-Sireru imbricate belt.

3.2.3 Sepik Shear Zone

A detailed tectonic analysis of the Sepik depression is beyond the realm of this study. However, in the present context; i.e., relative to transcurrent movements, it is worthy of some consideration at this point. As I pointed out at an early stage, the Sepik depression and its extensions the Meervlakte and the Ramu-Markham depression is one of the major physiographic lineaments in the world (1300 kilometers long). Similar linear depressions of this type are invariably associated with transcurrent movement; e.g. the Great Valley-Gulf of California complex, the Rocky Mountain trench, the Longitudinal Valley of Taiwan and many others as well.

For this reason and in view of strong evidence of transcurrent elsewhere in the orogen, it is not unlikely that there has been considerable transcurrent movement along the Sepik. Since this lineament parallels both the cordilleran and foreland shear zones it is suggested that such movement would also be in a sinistral sense.

I have already described in the case of the cordilleran and foreland shear zones how deep-seated lateral movements can be expressed at the surface as a series of en échelon and sigmoidal folds. However, depending on physical factors such as the rate of stress application, confining pressure and temperature, it is possible for similar lateral movements to be manifested at the surface in a series of en échelon tension fractures. In 1919 Chamberlin suggested that deep-seated sinistral shearing gave rise to the outstanding zone of en échelon tension fractures in central Montana known as the Lake Basin fault zone.

It is possible that the Sepik-Meervlakte depression may have in part originated in a very analogous manner; i.e., as a series of en échelon tension fractures related to fundamental sinistral simple shearing at depth. It is important to realize that although transcurrent movement may occur along vertical shear surfaces at depth, the strain pattern must change in the uppermost layers of the crust owing to the fact that rocks are weaker in tension than in shear and hence, the relatively common superficial pattern of en échelon tension fractures. However, pre-existing weaknesses in or near the direction of shear may cause the rupture threshold for shear in that direction to be reached before the rupture threshold in tension. Such major anisotropies are always present in the crust in

regions where shearing is directly expressed at the surface as a discrete fracture zone. For instance the Rocky Mountain trench coincides with the transition between the miogeosynclinal and eugeosynclinal realms, the boundary of the North American shield and finally the eastern margin of the Nevadan batholiths.

However, it is my opinion that deep-seated shearing is likely to be expressed in the former manner along the Sepik-Meervlakte depression; i.e., primarily by en échelon tension fractures. The pattern of this deformation is shown in Figure 31 in which the tensional fractures develop with an angle of about 45° to the zone of shear below. Some shear fractures in the conjugate direction might also be expected to develop as illustrated. Continued shearing would cause the development of new fractures, growth and finally coalescing of fractures. This fracturing, coupled with extension as was envisioned for the development of the Papuan geosynclinal system, could produce extensive fragmentation and trough-like sinking above the deep-seated shear zone. The Great Ice Chasm of the Filchner Ice Shelf in Antarctica (Wilson, 1960; Plate 6b) developed in exactly this manner.

3.2.4 Ramu-Markham Shear Zone

In addition to these three main zones of trans-current movement, it is possible that several other important physiographic and structural zones are associated with horizontal movements. Probably the most important of these zones is the Ramu-Markham depression which trends northwest from the Huon Gulf over 300 kilometers to join the Sepik depression. Although at first sight the Ramu-Markham and the Sepik depressions appear to form a continuous physiographic unit or lineament, closer examination

reveals that there are considerable morphological contrasts between the two features (Section 1.1.1). In addition there is a considerable difference in the trends of these two lineaments; viz., east-west in the case of the Sepik lineament compared to the northwestward trend of the Ramu-Markham line; thus they intersect with an angle of about 25 degrees.

On the basis of these two considerations, it is thought that there may be a significant difference in the types of horizontal movement occurring along these two lineaments. Referring to the stress diagram which was inferred for the central cordilleran region on the basis of the fold pattern of the main anticlinoria (Fig. 20) it can be seen that the Ramu-Markham line coincides almost directly with the compression direction. The strain pattern for the same region also suggests that some element of conjugate, dextral transcurrent movement may be present along this zone; i.e., the Finisterre, Sarawaged and Adelbert blocks would move southeastward relative to the main New Guinea cordillera. Movement of this nature is substantiated to some extent by the first motion studies of Ritsema and Veldkamp (1960) which indicate that in eastern New Guinea most earthquakes seem to be caused by a wrench movement of the Pacific Ocean to the south-southeast relative to the blocks south of it.

The relationship between the Ramu-Markham and the Sepik depressions is one of the most difficult tectonic problems in New Guinea and I must admit some reservations about the validity of my proposal. It may be possible that the two lineaments merge rather than intersect and the movement along the entire zone may be

in the sinistral sense. Only additional field mapping will provide a solution to this problem.

It should be noted that there is a strong possibility that extensional movements such as gave rise to the Papuan geosynclinal system may still be active along the Ramu-Markham line. One important line of evidence supporting this possibility is the pronounced negative free-air anomaly which has been detected along this zone by a recent gravity survey conducted by Mr. John Shirley of the Geology Department of the University of Tasmania. The magnitude of the anomaly ranges between -100 and -200 milligals and may be due to very thick accumulations of young, light sediments such as are commonly associated with modern rifting zones.

The important thing to realize, if extension and simple shear movements are concurrent in this zone, is that their effects will be in opposite directions; i.e., the extension will tend to open the rift, while compressional stresses related to simple shear will tend to close it. This dynamic balance may explain the striking morphologic contrasts between the Ramu-Markham and Sepik depressions, particularly the narrow, constricted appearance of the Ramu-Markham line relative to the much wider Sepik depression. The orientation of the Sepik zone is such that extensional movements perpendicular to its length would not be retarded by compressional simple shearing stresses to the same extent as they may be along the Ramu-Markham line.

3.2.5 Amount and Age of Lateral Movement

Having examined the patterns of deformation and the

morphological features of the New Guinea orogen which suggest important simple shear deformation at depth, we are faced with two important questions. The first and most difficult, perhaps insoluble question, is how much movement has there been along these zones? Finally, how long has this movement been in operation?

Amount of movement.-- At present and on the basis of study in western Papua and New Guinea alone it is nearly impossible to make a reasonably accurate estimate of the amount of lateral movement along any of these postulated zones. In the first place geological mapping in Papua and New Guinea has not yet reached the level where the quality or quantity of information would enable the recognition of offset stratigraphic, petrologic or structural elements on either side of a transcurrent zone.

Even with far more detailed mapping and petrological work, it may not be possible to match offset elements with the relative ease which has been shown by investigations in Scotland and California, because the patterns of transcurrent movement are quite different. In the case of Scotland, for instance, it is necessary only to match the Foyers and Strontian granites and the associated metamorphic zones to establish the net slip along the Great Glen fault, a discrete fault zone. However, in New Guinea the surface expression of deep transcurrent movements are spread across very wide zones and the deformation might be aptly described as smearing rather than shearing. In such a situation it will not always be possible to recognize reliably stratigraphic, petrographic or structural disjuncts as has been done by Kennedy (1946) in Scotland and Crowell (1962) in

California. A new set of criteria will have to be established.

Eventually, it may be possible to arrive at some semiquantitative estimate of the amount of lateral movement at depth by first estimating the amount of strain of structures which are the surface manifestations of the deep-seated shearing; e.g., the en échelon anticlines developed in the cordilleran shear zone. Here too, there would be considerable uncertainties and such methods would need to be tested in areas where the detailed structure is much better known than in New Guinea and preferably in an area where the amount of wrench-fault movement is already known.

Age of lateral movement.-- On the basis of the foregoing discussions, it is quite certain that sinistral simple shear was an important contributing element in the deformation which occurred during the Plio-Pleistocene stage of orogenesis. This is particularly witnessed by patterns of sigmoidal and en échelon folding in both the central and western cordilleran regions which can only be attributed to internal rotations about a vertical "roller" axis which is typical of simple shear deformation. However, as yet there has been no concrete evidence found within the limits of western Papua and New Guinea which would substantiate the presence of these movements in the earlier geosynclinal phases of diastrophism. This, of course does not mean that pre-Plio-Pleistocene simple shearing did not occur. It is, in fact, plausible to suggest that important horizontal movements of this type have taken place, possibly beginning as early as the Cretaceous. However, the considerable implications of such movement are external to the present problem and

will be considered in Section 3.4.

It is concluded that the structural patterns within the orogenic belt and first motion studies of earthquakes indicate that simple shear deformation has played a significant role in the tectonic evolution of the region. At present it is impossible to make any reliable assessment of the amount and age of the movement.

3.3 ROTATIONAL DISPLACEMENTS

Since 1938 Carey has suggested that the rotational displacement of quite large crustal blocks represents an important element in the development of many orogenic systems. He has clearly shown how many seemingly anomalous tectonic problems can be solved, if one accepts the validity of such rotations. This is true irrespective of whether the rotations are caused by the expansion of the earth, subcrustal convection currents, the zonal rotation of the earth, or any similar mobilistic mechanism.

There is considerable evidence in the structural patterns of the Purari River region indicating that such rotational movements have affected the development of the Papuan foreland folded belt. The Purari River region forms the eastern boundary of the portion of the foreland folded belt which has been examined in particular detail in the preceding sections and separates it from a quite different structural province to the east in the Kukukuku lobe.

3.3.1 Purari Orocline

As I have mentioned before the Purari River region of the Papuan fold belt is the epitome of a structural knot. To the west of the Purari River the structural grain of the country is nearly east-west (Plate 1 and Fig.23). To the east in the Kukukuku lobe the structural

grain is essentially north-northwesterly. The external structures of these regions, especially the Kuku and Bevan faults, are continuous through the bending zone. They trend east-southeast in the western region but to the east swing through nearly 90 degrees and trend north-south, paralleling the eastern margin of the Delta embayment. The nature and origin of this great bend is one of the most outstanding problems in the tectonics of Papua. Few fold belts in the world show such a gross change in the tectonic trends.

The apparent intersection is not caused by the superposition of two structural trends of different ages. The structures constituting these two opposed trends are developed in the same rocks; generally Lower Miocene to Pliocene, and have similar structural characteristics. Both trends are largely the result of Plio-Pleistocene tectogenic processes.

The problem with which the geologist is faced and which was realized by Carey in 1938 is whether or not this remarkable change in trends is inherent from the original configuration of the geosyncline or alternately represents a superimposed bend in an originally nearly linear belt of structures. Carey in light of considerable field study and taking cognizance of regional tectonic relations, felt that the evidence favored the latter possibility. Indeed, Carey's orocline concept (1955) was conceived through his study of this unique region. Considerable geologic mapping in the Purari River area since Carey's initial surveys has made it possible to extend the application of the orocline hypothesis in the Papuan foreland folded belt.

Some of the most useful information of this nature has come from the survey of Kent and Rickwood (LW, 1956) northward beyond the Purari River into a region which was unexplored when Carey made his analysis of the tectonics of the so-called Purari bend. Perhaps the most important discovery of this survey was the existence of the Hau-Toila fault zone which has been described in a previous section. To recapitulate briefly, this fault zone extends northward from the Purari-Aure River junction for nearly 50 kilometers and truncates eastwest-trending folded structures, putting them into juxtaposition with the north-south structures (Fig. 23) within the Aure-Tsoma graben. The Hau-Toila fault zone, together with the northeast-trending Aure fault and the intervening structures, form a tectonic province which is consistent with and, indeed, can only be explained by the orocline hypothesis. In a situation analagous to anticlinal arching where tensile stresses accumulate in the convex side of the bent arc; so, in the bending of an orocline one would predict tensile stresses on the outer or convex side of the orocline. It is my suggestion that the wedge-like graben defined by the Hau-Toila and Aure fault zones was produced by tensile stresses related to the bending of the Purari orocline.

This hypothesis is supported by several lines of evidence:

1. The rocks within the wedge are generally younger (Middle Miocene) than those rocks on any of the bordering rims (Lower Miocene to Cretaceous).
2. The fault and flexure systems bordering the wedge especially in the Hau-Toila zones have the characteristics of normal faults bordering a graben. The part of the Aure fault bounding the southeast side of the wedge

has not been studied in enough detail to make a judgement but may well be a normal fault.

3. The peculiar fault-fold pattern within the wedge itself does not appear to be related to the truncated folds on the west nor does it appear to be related to the northerly-trending structures in the Kukukuku lobe. Although it may be argued that the folds and faults in the wedge, like those in the Kukukuku lobe, have a general northerly trend, it is important to note the manner in which they radiate from a common center near the Aure-Purari River junction. I propose that these structures have been produced by sagging and refolding of the surficial sedimentary layers into the void produced by the opening of the Aure-Tsoma wedge graben. On the north the graben is terminated abruptly by the eastwest-trending Gorga fault zone. The tensile stress was probably relieved by sinistral movement along this fault. It is quite possible that lateral movement along other major fault zones in the north; e.g., the Bismarck fault zone also played a major role in relieving the stress produced by the bending. There was probably also lateral movement along faults on the concave side of the bend; viz., the Bevan and Kuku faults, which probably predate the bending.

3.3.2 Origin of the Purari Orocline

I have been quite unsuccessful in attempts to explain these peculiar structures by conventional means and am convinced that the Purari bend and the Aure-Tsoma wedge graben could have been produced only by the rotational displacement of certain elements within the regional tectonic framework of New Guinea, specifically the clockwise rotation of the Owen Stanley block relative to the central cordilleran region (Fig.32).

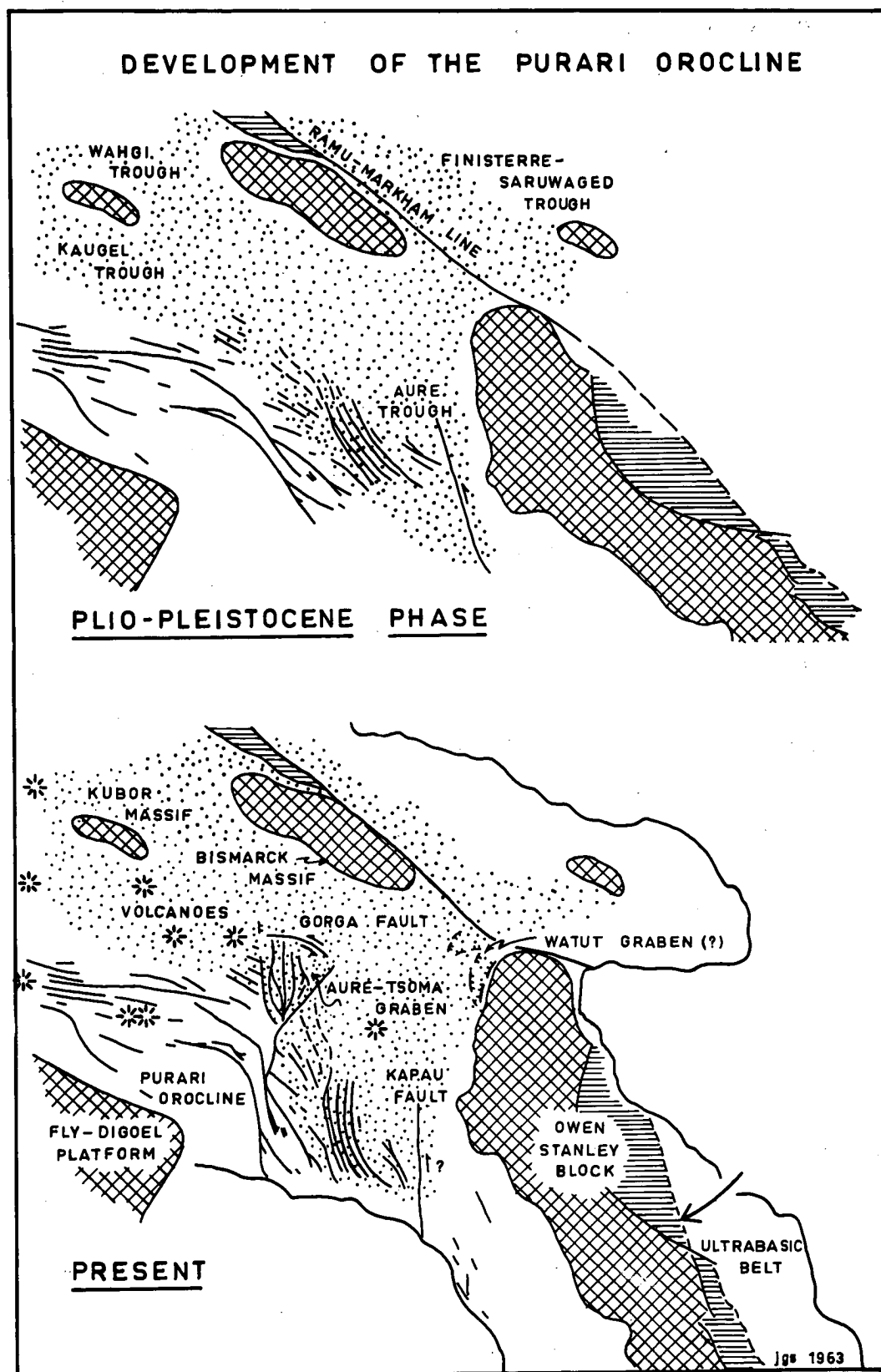


Figure 32

The Owen Stanley block is the term which I have applied to the extensive crystalline core of the New Guinea cordillera in central and southeastern Papua. A detailed study of the Owen Stanley block is beyond the realm of this study. However, in order to better appreciate the development of the Purari orocline it is necessary to review the general nature of this structural province.

The block is composed mainly of regional metamorphic rocks; the Owen Stanley Metamorphics (E.R. Stanley, 1923), which are probably Paleozoic, although some limited occurrences in the Morobe region are Cretaceous (Glaessner, 1949). In this latter region the metamorphics are intruded by granodiorite stocks and batholiths (Fisher, 1944). The metamorphics are flanked on the northeast by an extensive belt of ultrabasic rocks which were mentioned in Section 1.10.2 and are included in the Owen Stanley block. Tertiary sedimentary and volcanic accumulations overlap both the northeastern and southwestern margins of the Owen Stanley block. The tectonic character of this block is quite similar to that of the Kubor and Bismarck massifs, although it is considerably larger than either of these latter structures.

In addition to the configurations of the Purari bend and the Aure-Tsoma wedge, this rotation is also suggested by the morphology of the Watut River valley, a tributary of the Markham River; the diverging trends of otherwise similar structural belts in the Owen Stanley block versus those associated with the Kubor and Bismarck massifs, and finally the configuration of the Huon Gulf and the Solomon Sea.

Trends of the main cordillera.-- In general the trend of the central cordillera is northwestward while the orogenic trend of the eastern cordillera or the Owen Stanley block is north-northwest. Hence, the two trends intersect an angle of 25-30 degrees which at first examination would not appear to be a significant orogenic bend. However, on closer examination it can be seen that this change of trends takes place over a distance of 120 kilometers in the Lower Markham River region and to either side of this inflection the trends are consistent for at least 320 kilometers. The bend is also reflected in the overall configuration of the great ultrabasic belt developed along the northeastern flanks of the Owen Stanley Ranges and the Bismarck Range in the central cordillera.

Watut graben.-- The bend in the New Guinea cordillera developed in a region which during the Lower Miocene was a gap in the line of cordilleran geanticlines, i.e., Kubor-Bismarck massifs and the Owen Stanley block, through which the Kaugel and Aure intrageosynclinal troughs were connected with the geosynclinal system of the northern ranges. This gap acted as a zone of weakness or hinge about which the Owen Stanley block rotated. The morphology of the Watut Valley, which is developed in this hinge zone, suggests that failure was by tension. The Watut Valley, a southern tributary of the Markham, forms a deep re-entrant which extends nearly 48 kilometers south-southwestward into the New Guinea cordillera. In this roughly triangular area the elevations are no more than about 300 meters in contrast to the elevations up to at least 2800 meters on the rims of the valley. I suggest that this valley may be another wedge-shaped graben which is due to tensional stresses produced by rotational movements of the Owen Stanley block.

The rotation of the Owen Stanley block is also consistent with the morphology of the Huon Gulf and the Solomon Sea which were interpreted as sphenochasms by Carey (1958). The implications of these structures will be referred to at a later stage.

Although it seems quite likely that the bending of the Purari orocline has in fact been caused by the rotation of the Owen Stanley block, the exact nature of linkage mechanism between the Owen Stanley block and the Purari bend is not completely understood, mainly because of the lack of good structural information in particularly critical areas. There are at least two pivot points for this rotation; the main point is thought to fall along the axis of the Owen Stanley block near its northwestern extremity in the Watut Valley as indicated in Figure 32. A conservative estimate of clockwise rotation about this point would be about 20 degrees. This is the figure which has been used in the tentative reconstruction of the pre-rotational configuration of eastern New Guinea.

An apparently secondary pivot is located in the Purari River region as indicated by the inflection in the structural grain and the configuration of the Aure-Tsoma graben. It is important to note that this pivot coincides closely to the northeast corner of the Fly-Digoel platform and it appears likely that this stable block served as a buttress around which the foreland structures were bent. The angular displacement of the foreland folded structures, however, is generally greater than the amount suggested for the rotation of the Owen Stanley block (20 degrees). An average figure would be about 50 degrees. Some of the folds in the interior of the Kukukuku lobe which are thought to be older (early Pliocene or even Upper Miocene)

than those closer to the external margin of the foreland belt (Plio-Pleistocene) appear to have been rotated even more. Hence, it appears that the Kukukuku lobe may have rotated to some extent independently of the Owen Stanley block or else the rotation of the latter was amplified in the Kukukuku lobe by some mechanism which, as yet, is not apparent. However, even if the Purari orocline is unbent a conservative 20-30 degrees as shown in Figure 32 the resulting configuration of the folded belt would fall within the realm of the variations in tectonic trends that would be normally expected owing only to irregularities of the sedimentary basin. This reversal would be sufficient to close the Aure-Tsoma graben.

In general then, it seems that the Owen Stanley block has been rotated about a series of pivots; all of which are situated in a zone extending from the head of the Huon Gulf southwestward to the northeasternmost corner of the Fly-Digoel platform. The broad outlines of this zone were recognized by Carey in 1938. At that time it was referred to as the Purari bending axis.

In addition to the bending and tensional rifting there is also likely to have been some translational displacements associated with the rotation of the Owen Stanley block. Comparing Figures 32a and 32b, it can be seen that in the reconstruction the southwest corner of the Owen Stanley block is situated to the southeast of its present position relative to the folded structures of the Kukukuku lobe. Assuming the validity of my reconstruction and rotation about the pivots which I have specified, this relationship implies the necessity for sinistral translation between the Owen Stanley block and the Kukukuku lobe. Such translational movements may have

been relieved along the Kapau fault zone which is a major structural line separating two very different structural and sedimentational provinces; i.e., the Kukukuku lobe and the Lakekamu embayment region to the east. This fault zone has played a significant role in the development of both these regions; it would not be unlikely that some translation may have occurred along that zone of weakness in response to the rotation of the Owen Stanley block.

Transverse movements were probably also associated with rotation around the Purari pivot and would be expected to have occurred along the base of both the Aure-Tsoma and Watut wedge grabens. Referring again to Figure 32b the northsouth-trending structures within the Aure-Tsoma graben are truncated on the north by the easterly Gorga fault zone. It is suggested that transcurrent movement, probably in a sinistral sense, occurred along this zone to relieve the east-west extension accompanying the opening of the wedge graben. Similar movement related to the opening of the Watut wedge would be accommodated along the Ramu-Markham line.

3.3.3 Rotation of New Britain

Carey (1938;1958, Fig.41a) suggested that New Britain was originally situated immediately to the northeast and parallel to the Owen Stanley block. In this respect the New Britain block is considered as once being contiguous with the Adelbert-Sarawaged-Finisterre trend and was a part of the so-called northern massif which formed the margin of the Mesozoic Papuan geosynclinal system. At that stage the two massifs were separated by a zone of fundamental crustal weakness which was a southeasterly continuation of the Ramu-Markham line. The

high mobility of this zone is indicated first by the fact that it formed the northern boundary of the Mesozoic Papuan geosynclinal system and secondly by the fact that great masses of ultrabasic materials penetrated the relatively surficial layers of the crust along this zone (Owen Stanley ultrabasic belt). At a later critical stage in the tectonic development of New Guinea crustal rifting and stretching had proceeded to such a degree that the continental crust in eastern New Guinea was finally parted along this zone of weakness and exposed oceanic-type crust in the gap between the Owen Stanley and New Britain blocks. The formation of this structure, the Solomon Sea or Huon sphenochasm (Carey, 1958), was accomplished mainly by rifting aided by counter-clockwise rotation of New Britain. The sense of rotation of this latter block is opposite to the apparent rotation of the Owen Stanley block. However, this anomalous relation will be shown to fit into the gross pattern of horizontal movements in the Australasian province.

3.3.4 Implications of Rotation

If the Owen Stanley block has in fact rotated clockwise relative to the central cordilleran region in the late Tertiary, such movements would have considerable implications relative to the original configuration of the intrageosynclinal troughs and other tectonic elements within the Papuan geosynclinal system. The Kaugel and Aure troughs which are crossed by the Purari bending axis are likely to have been strongly affected. At present there is a considerable angle (about 50 degrees) between the trends of these two troughs which meet in the upper Purari River region. However, if the Purari orocline is unbent, the Aure trough is seen to be an eastern extension of the Kaugel trough.

However, this reconstruction opens another difficult problem. At present there are no structures flanking the southern margin of the Aure trough which would compare to the Erave-Wana swell, the Omati trough or the Fly-Digoel platform, all of which border the southern margin of the Kaugel trough. I suggest that one need only look beneath the Coral Sea Plateau for very similar structures, which were also detached from the southern margin of the Owen Stanley block by rifting and rotation.

3.3.5 Age of Rotation

The rotation of the Owen Stanley and New Britain blocks has probably been accomplished only recently. This is mainly suggested by the fact that many of the bent structures in the Purari orocline, notably the Puri anticline, Bevan and Kuku faults, involve Pliocene rocks. Hence, if one accepts the suggestion that the bending of the Purari orocline is related to rotation of the Owen Stanley block; then it can only be concluded the rotation was accomplished, at least to a very large extent, during the latest Pliocene and early Pleistocene and probably coincides with the main orogenic phase of diastrophism and the upheaval of the main New Guinea cordillera. It is important to note that if, in fact, the formation of the Huon sphenochasm coincides with the main phase of uplift of the central cordillera, it implies that extensional stresses existed throughout New Guinea during orogenesis. The significance of this tentative association between extensional stresses and orogenesis will be pursued in detail in the following section concerning the origin of vertical movements within the geosynclinal system.

There is currently a considerable amount of seismic and volcanic activity in the eastern New Guinea-New Britain region and it is very likely that extensional movements of the earth's crust are still active there. The line of volcanoes which extends northwest from the western tip of New Britain and includes the active volcanoes Bam and Manam (Map 1) may be developing along an incipient extension fracture.

3.4 DEVELOPMENT OF HORIZONTAL MOVEMENTS IN AUSTRALASIA

Since 1938 Carey has argued that horizontal displacements of global proportions have occurred between crustal blocks in the Indonesian and Melanesian regions of the Pacific. Specifically he has proposed that, beginning in the late Mesozoic, the Australian block has moved eastward relative to the Asian continent to the north.

If, in fact, movements of this nature have occurred, then they would be expected to have had a considerable effect on the late Mesozoic and Tertiary development of the Papuan geosynclinal system. Such movement should be especially well expressed by the structural patterns within western Papua and New Guinea. Consequently, it is appropriate to examine the basic principles of the movements proposed by Carey and their implications in relation to the diastrophic development of western Papua and New Guinea or vice versa.

Carey (1958) has drawn attention to the fact that paleomagnetic data indicate that during the Jurassic Australia was situated off the east coast of India some 6000 kilometers west of its present position. A critical paleogeographical study of Gondwanaland led Ahmad (1961) to conclude that, "The similarities in the basins ... the associations of similar rock types and minerals in the

basement complex, the occurrence of identical Cretaceous fauna, etc. All go to show that Australia was much closer to India, and both were closer to Africa, than they are today." Ahmad also expressed the opinion that the bulk of the movement or "drift" between India and Australia began soon after the end of the Cretaceous.

According to Carey (1938, 1958) the eastward shift of Australia is implied explicitly by the gross structural pattern of the Indonesian-Melanesian region. Such features include the outstanding offset of the Pacific margin (Fig. 33) from the Moluccas eastward through 60° to Samoa, as well as the sinistrally coupled Indonesian oroclines; i.e., the arcuate bends of the Indonesian Archipelago. The displacement of the Pacific margin does not occur along a discrete line but is spread over a very wide belt which embraces the New Guinea orogenic system. Because New Guinea is located in this shear zone separating Australia and Asia, the structural patterns of the island should and, in fact, do show that sinistral shearing movements have played an important role in the tectogenic development of the orogen. In previous pages I have shown that the anticlinorial structures of the western and central cordilleran regions bear the stamp of such deep-seated lateral movements and are, hence, consistent with the proposed eastward drift of Australia. The geometric relationships between the superficial strains and the deep-seated zones of shear have been developed in detail in Section 3.2 (Fig. 31).

Recent paleomagnetic studies, Irving and Green (1958) indicate that in addition to having shifted eastward Australia has rotated counterclockwise since the Jurassic. My colleague, R.P.B. Pitt, has made preliminary paleo-

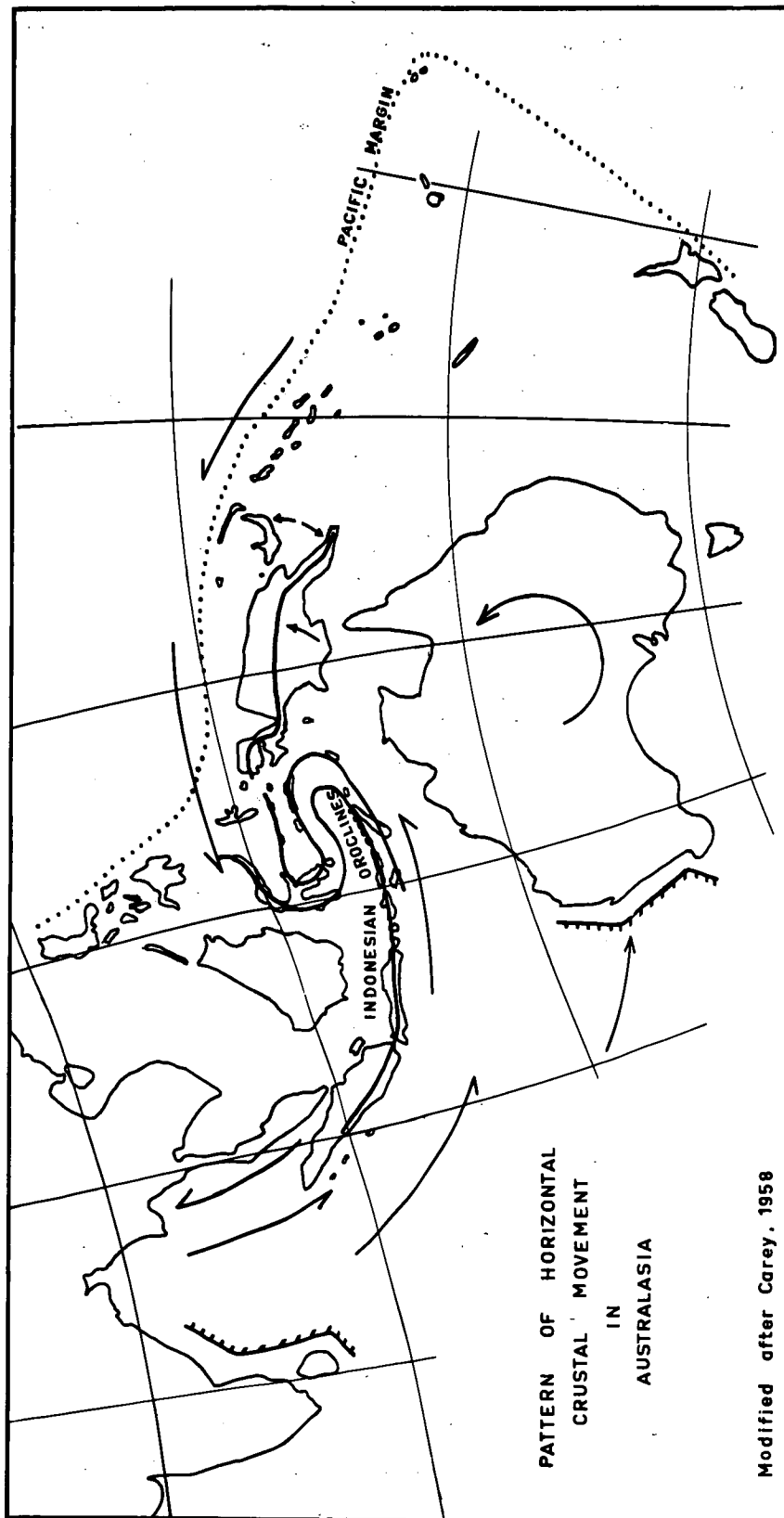


Figure 33

magnetic determinations from rocks collected in New Guinea which suggest that it has also been rotated counterclockwise. This rotation is consistent with the sinistral lateral movement along the equatorial shear belt, but appears to contradict the rotation I have proposed for the Owen Stanley block; i.e., clockwise relative to the central and western cordilleran regions. However, it is possible that this discrepancy is only superficial and the main cordillera of central New Guinea may have been rotated counterclockwise while the Owen Stanley block lagged behind. Thus, it is possible that the northwest trend of the Owen Stanley block is nearer to the original trend of the Papuan geosynclinal system.

Indeed, Carey (1958) proposed that the original trend of New Guinea was north-south, and that it was situated considerably north and east of the Australian continent during the Cretaceous. The two masses were thought to have come into juxtaposition by translation along a system of conjugate shears. However, I prefer to think that the Papuan geosynclinal system was never far removed from the Australian craton. Prior to the disruption of Gondwanaland in the latest Cretaceous or early Tertiary it is thought to have bordered the northern margin of the incipient Australian continent. The reconstruction does not preclude the possibility that the original trend of the geosyncline was northerly.

Thus as a result of eastward drift and rotation of Australia and New Guinea, the main trunk of the cordillera was rotated counterclockwise through nearly 90° while fragments such as the Owen Stanley block lagged behind and give the impression of local rotation in the opposite sense. On the other hand New Britain, which is situated

closer to the equatorial torsion zone, was rotated as much as 120° .

3.5 ORIGIN OF HORIZONTAL MOVEMENTS

In the preceding pages I have written that the complex system of horizontal movements, that have played a fundamental role in the development of the New Guinea orogen, can be differentiated into two modes of deformation: extension and simple shear; and two modes of displacements: translation and rotation. If this strain analysis is correct, it then places significant restrictions on the nature of the processes which could provide the ultimate origin of the horizontal movements.

In the first place the presence of horizontal crustal movements rules out the "fixistic" tectonic mechanisms (van Bemmelen, 1954) advocated by many investigators, particularly in the Soviet Union. There are two mobilistic geotectonic hypotheses which could conceivably explain the horizontal crustal movements which are manifested within the New Guinea orogen: expansion of the earth and subcrustal convection currents. The possible application of both these basic mechanisms to the New Guinea orogen has been mentioned in the previous sections describing the nature of the extensional rifting of the crust. In the following sections the application of these hypotheses to the total horizontal deformation of the crust within New Guinea, including simple shear and rotation, will be considered briefly.

3.5.1 Tethyan Torsion System

The hypothesis of the earth's expansion as advocated by Egyed, Heezen and Carey is a quite adequate mechanism for the formation of geosynclinal belts by crustal extension (i.e., rifting and stretching). Furthermore, the horizontal simple shear deformation, as well as the translational and rotational displacements, which are implied by the structural patterns in western Papua can also be produced by such a mechanism.

The simplest mechanism for the generation of simple shearing stresses in the earth's crust due to expansion is as follows. The equatorial regions of an expanding earth would move away from the axis of rotation, hence, the radius of rotation and the moment of inertia would increase. The moment of inertia would not increase in the polar regions since expansion would be along the axis of rotation. This process would cause zonal variations in the rate of rotation of the earth particularly in the lower mantle and in the core. The adjustments between these zones would probably be by viscous drag because in the time involved in expansion these materials would behave as a fluid. The zones of flow would in turn be coupled with the more rigid crust and upper mantle and would there set up simple shearing stresses. The disposition of the shear zones would depend primarily upon the distribution of expansion throughout the earth; i.e., whether it was uniform or concentrated in certain regions of the globe.

Carey (1958) has postulated on empirical grounds based on the orocline concept that the main zone of rotational adjustment occurs in an equatorial belt which

he has called the Tethyan torsion system. Extensive study of global geotectonic patterns led Carey to conclude that since the Paleozoic the southern hemisphere has been shifted some 50 degrees farther east (i.e., sinistrally) than the northern hemisphere and, thus represents one of the most fundamental structures of the earth.

Conceivably, subcrustal currents due to some physiochemical gradients within the lower mantle and core could produce the identical simple shearing stresses in the upper mantle and crust. In fact, Carey (1963) has suggested that independent reciprocal subcrustal circulation within the two hemispheres could well give rise to the Tethyan torsion system.

The foregoing discussion has been kept short and quite general because of the complexity and vast uncertainties associated with the problems of the earth's expansion, convection currents and other basic processes which would promote large-scale horizontal movements of the earth's crust. Rather, I have concentrated my efforts on description of the structural features of western Papua and New Guinea which imply such movements. These studies, as well as Carey's worldwide geotectonic analyses, point to the conclusion that such horizontal movements have played a role in the diastrophic evolution of most major orogenic belts, irrespective of the ultimate origin of the forces producing these movements.

4. ROLE OF POSITIVE VERTICAL MOVEMENTS IN DIASTROPHISM

In Section 3.1 I discussed to some extent the nature of negative vertical crustal movements which characterized the taphrogenic phases of diastrophism in Papua and New Guinea and which were intimately related to extensional stresses in the earth's crust. The following section is devoted to an analysis of the nature and origin of positive vertical movements within the Papuan geosynclinal system. I will first analyze the nature and origin of the subordinate positive movements which occurred during the taphrogenic phases of diastrophism when the general tendency of movement was negative. This will be followed by an examination of the nature and origin of the positive movements which were paramount during the orogenic phase of diastrophism. Two mechanisms which might have been capable of causing the rise of geanticlines within Papuan geosynclinal system and the ultimate uplift of the New Guinea cordillera are discussed in rather general and speculative terms.

4.1 NATURE OF POSITIVE VERTICAL MOVEMENTS

4.1.1 Taphrogenic Phase of Diastrophism

Despite the strongly negative tendency of the vertical crustal movements which characterized the Mesozoic to Middle Miocene geosynclinal development of western Papua and New Guinea, there were several regions within the mobile belt where positive movements were pronounced. As I have repeatedly argued the crystalline cordilleran massifs remained positive, although not necessarily emergent, throughout the entire geosynclinal development of the New Guinea cordillera. To the south in the central foothills region the Erave-Wana swell and the Darai swell represented positive geanticlines in an otherwise negative and sinking geosynclinal regime.

Erave-Wana and Darai swells.-- Study of the diastrophic framework of sedimentation in the central foothills region of western Papua indicates a very close spatial relationship between the main tectonic elements of the region: the Kutubu, Omati and Kaugel troughs; and the Erave-Wana and Darai swells. Specifically, each of the geanticlinal swells developed in a region which in a preceding epoch was the site of a deep trough, filled with a considerable accumulation of sediments. In this sense the vertical movements of tectonic elements in the

central foothills were of a typically oscillatory nature; i.e., geosynclinal sinking was followed by geanticlinal uplift. This particular sequence of vertical movement is quite common in other orogenic belts and according to Beloussov (1962), it is thought to be one of the fundamental regularities in the development of geosynclinal regions. I am in accord with this opinion and suggest that this relationship is a significant clue to the ultimate origin of vertical movements within a geosynclinal belt. As we shall see, it is especially consistent with orogenic hypotheses in which gravity is the primary driving force of differential vertical movements.

In order to understand the nature of these movements and attempt to solve the problem of their origin, it is necessary to review the tectonic history of the central foothills paying particular attention to the lateral extent of the tectonic elements which developed within this region.

In my opinion the basic foundation for the subsequent tectonic evolution of the region was laid out in the Mesozoic with the formation and growth of the Kutubu trough. As seen in Figure 17 this broad trough trended northwestward across the central foothills region from the Purari River region to at least the Star Mountains region of West Irian. A sedimentary thickness of 3000 meters and possibly much greater accumulated in this trough. The first indication of vertical oscillatory movements in western Papua is the character and distribution of the Paleogene rocks which suggest that geosynclinal sinking ceased and the mobile terrain was temporarily stabilized. Within the limits of our knowledge of the configuration of both the Paleogene quasi-platform and

the Kutubu trough, it appears that these features are essentially coincident in space (Fig.34). This observation indicates that the entire Kutubu trough was epeirogenically uplifted and stabilized.

The retrogressive phase of taphrogenesis in the Papuan geosynclinal system began in the Lower Miocene with the remobilization and subdivision of the old Mesozoic geosynclinal realm into three smaller but, nevertheless, important tectonic elements: the Kaugel and Omati troughs and the intervening Erave-Wana swell. Referring again to Figure 34 it is important to note that in the Lower Miocene the Erave-Wana swell developed directly over the axis of the Mesozoic Kutubu trough. In other words the negative tendency of this region became partially reversed and the central part of the Kutubu trough was uplifted to some extent.

In a similar context there is a very close spatial relation between the Omati trough, the Middle Miocene development of the Erave-Wana swell and the Upper Miocene and Pliocene development of the Darai swell which has culminated in the present configuration of the Darai uplift. In Section 1.5.2 the Omati trough was described as an elongate intrageosynclinal trough in which slightly over 3000 meters of limestone accumulated. The axis of this trough coincides approximately with the southern margin of the Kutubu trough, and in general it encroached somewhat southward onto the Fly-Digoel platform owing to the simultaneous rise of the Erave-Wana swell. However, the negative movements of the Omati trough were short-lived and by the Middle Miocene the nature of movement had again reversed, resulting in the rise of the prism of limestones which had been deposited in the trough. This

SPATIAL RELATIONS OF INTRAGEOSYNCLINAL TROUGHS AND SUBSEQUENT TECTONIC HIGHS

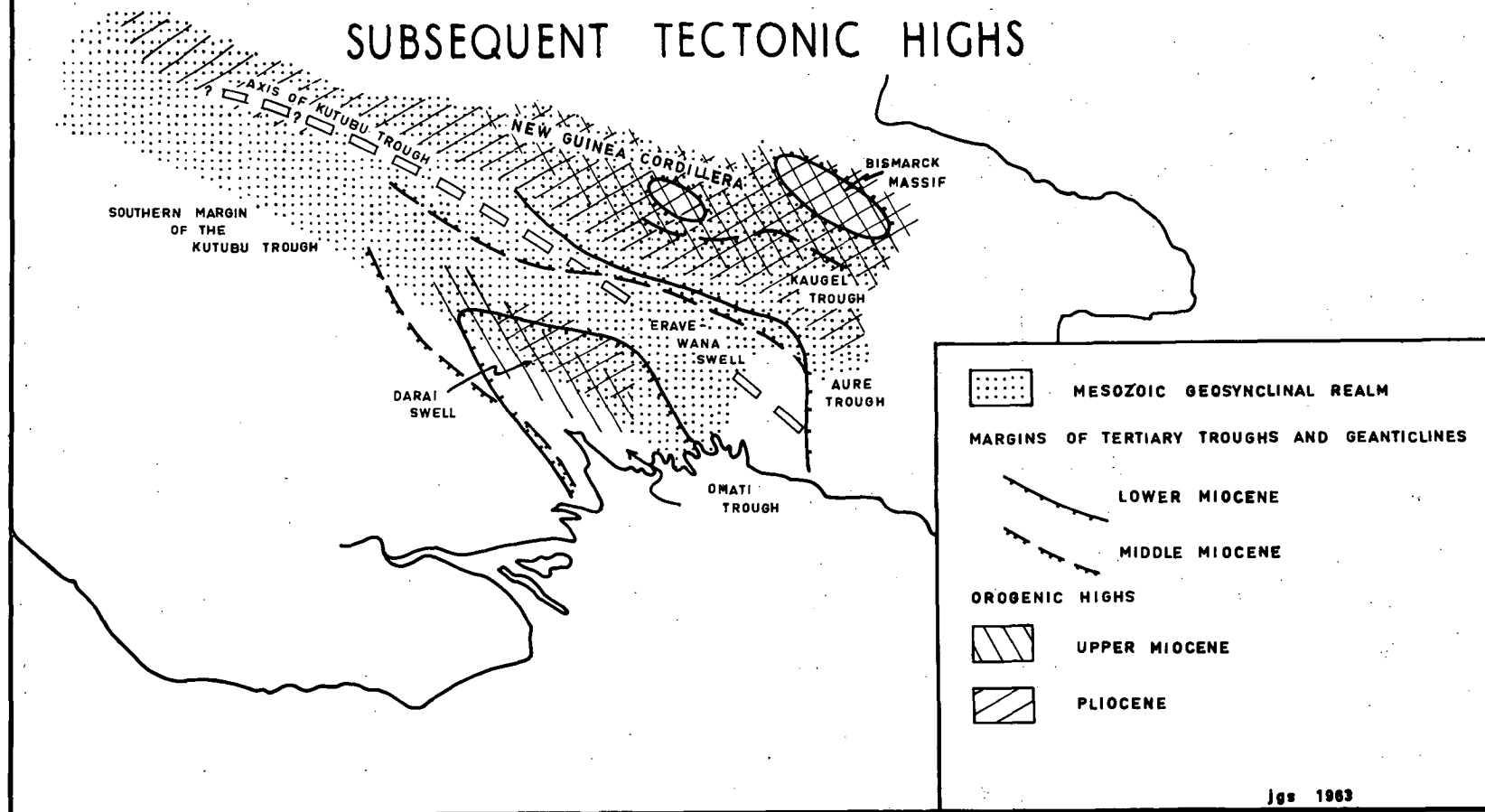


Figure 34

uplift is indicated by a comparison of the Middle and Lower Miocene diastrophic framework maps (Figs. 7 and 9) which show that the Erave-Wana swell had expanded a considerable distance southward in the Middle Miocene. The lateral extent of this expansion corresponds quite closely to the original extent of the Omati trough and is explained by the partial regurgitation or uplift of the thick limestone prism which became an integral part of the larger Middle Miocene Erave-Wana geanticlinal swell. In the Upper Miocene and Pliocene the rate of uplift within the Omati trough region exceeded that of the original sector of the Erave-Wana swell and it stood alone as a separate tectonic element, the Darai swell. In contrast to this, the northern margin of the swell began to sink and became the site of an exogeosynclinal trough (Purari basin) which formed along the southern margin of the central cordillera during the first stages of orogenic uplift in the Upper Miocene and Pliocene.

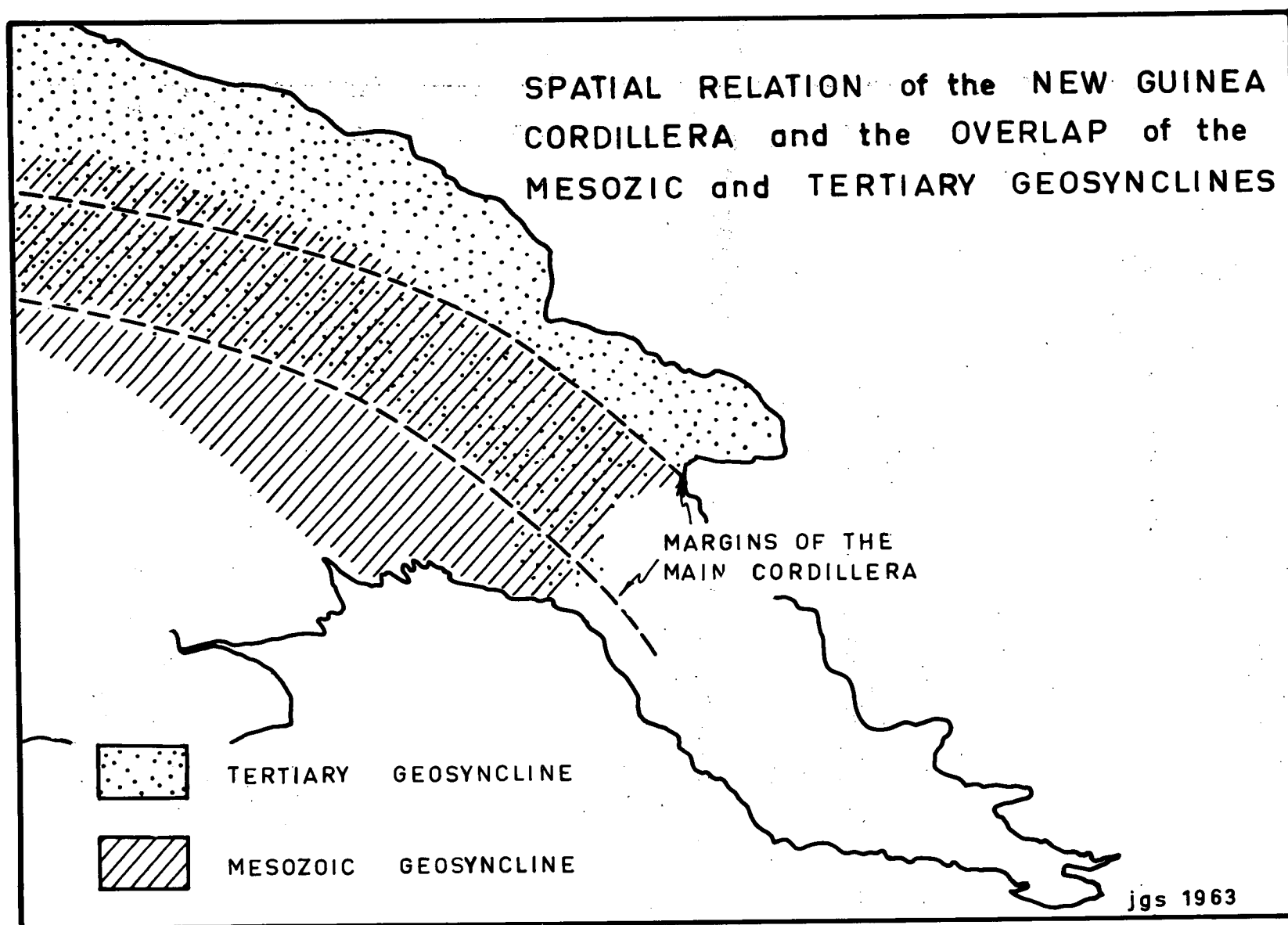
4.1.2 Orogenic Phase of Diastrophism

Main cordillera.-- In one very significant aspect the uplift of the main cordillera was very similar to the development of the geanticlinal highs in the central foothills region during the taphrogenic phase of diastrophism. This parallelism lies in the fact that all these positive welts grew out of regions which in previous diastrophic epochs were characterized by geosynclinal sinking and the accumulation of thick sedimentary sequences. Hence, the vertical movements of the main orogenic zone are also of an oscillatory nature. This is, of course, one of the oldest concepts in geotectonics, as it was recognized by James Hall in 1859. Nevertheless, it is a concept which is continually overlooked in many modern

hypotheses of orogenic development.

The only difference in the development of the orogen versus that of the geanticlinal swell stems from the continued greater mobility in the central cordilleran region, which has led to more pronounced differential movements, and a longer oscillatory cycle.

Inspection of Figure 35 shows that the late Tertiary to Recent uplift of the main cordillera occurred directly over the site of maximum Mesozoic and Tertiary geosynclinal sedimentation. Actually this zone of maximum accumulation represents the overlap of the Mesozoic and Tertiary Papuan geosynclinal systems. As I have described in some detail in previous sections, the Mesozoic mobile belt probably extended only as far north and northeastward as the present Ramu-Markham and Sepik depression and southward as far as the Turama River. During the Tertiary the rise of the Erave-Wana swell and the subsidence of the northern cordillera caused a generally northward shift of the eastern end of the Papuan geosynclinal system. Consequently, only the region now occupied by the main cordillera was the site of both thick Mesozoic and Tertiary geosynclinal accumulations. It is significant that this unique belt evolved into the main mountain system of New Guinea.

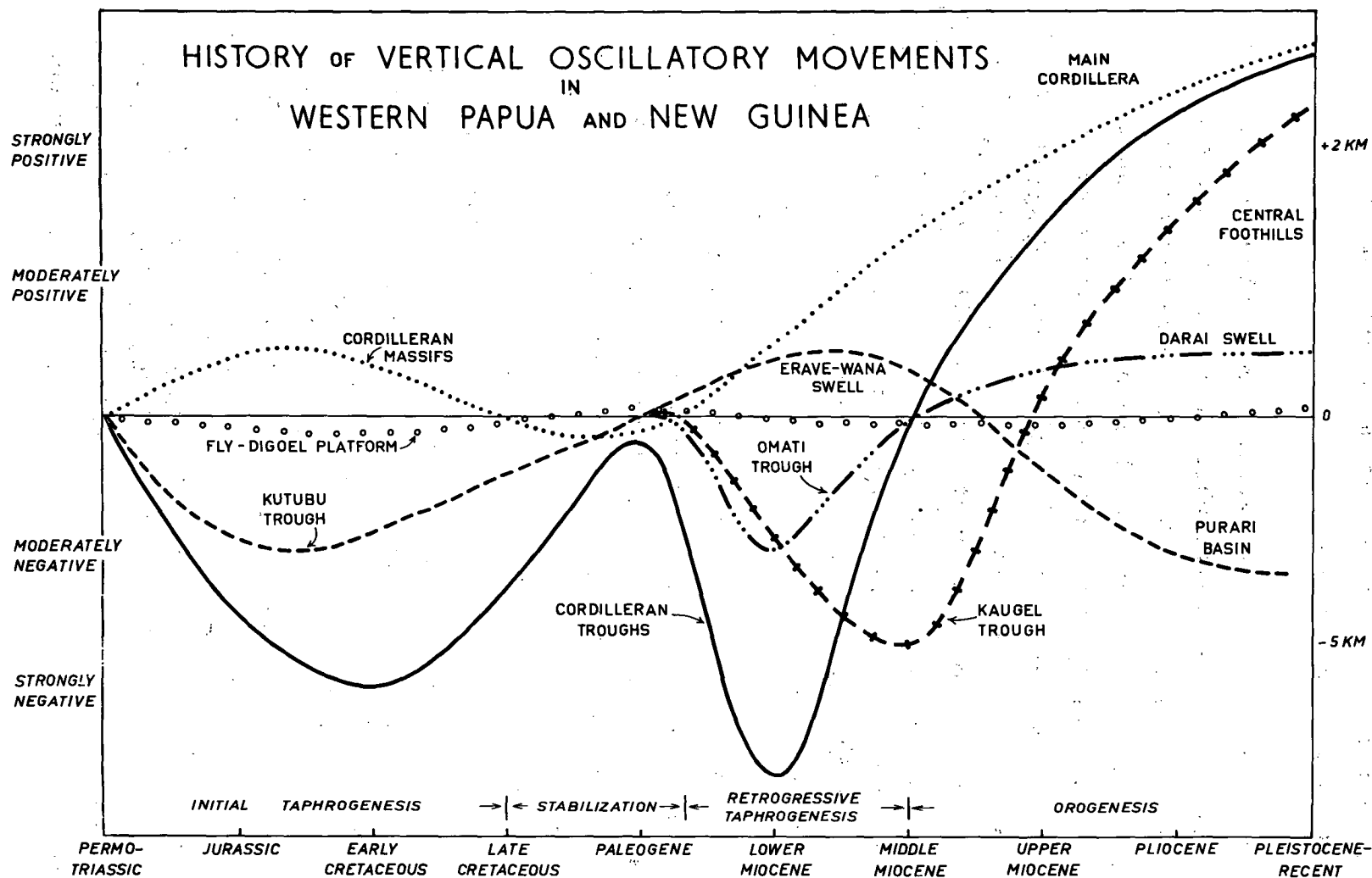


4.2 OSCILLATORY NATURE OF VERTICAL MOVEMENTS

The truly oscillatory nature of the vertical movements, which characterized the diastrophic evolution of the Papuan geosynclinal system, is clearly evident on Figure 36. The evolution of each main element in the diastrophic framework of New Guinea can be traced through a period of negative movement followed by a phase of positive vertical movement. It should be noted in this respect that positive vertical movements have been exaggerated on this chart for the sake of clarity, since the amplitude of positive movements represent only a small fraction of the total movement in a mobile belt; e.g., in the axial zone of the Papuan mobile belt the ratio of positive to negative vertical movement may be as small as 1:3 or even 1:5, whereas in Figure 36 they are shown to be about equal.

In general it can be seen that the oscillations were most rapid in the central foothills region. Specifically, the Kutubu trough was partially inverted and subdivided into smaller elements: the Omati and Kaugel troughs; and the Erave-Wana swell, and in turn these smaller structures were again inverted in a time equivalent to the inversion of the main eugeosynclinal axis of the central cordilleran region. However, amplitude

Figure 36



AMPLITUDE OF POSITIVE MOVEMENTS EXAGGERATED X3 RELATIVE TO NEGATIVE MOVEMENTS

of the vertical movements was much greater in the central cordilleran regions.

This chart also illustrates very clearly the four main phases in the diastrophic evolution of western Papua and New Guinea which were differentiated in Section 1.9. The Mesozoic phase of initial taphrogenesis is clearly defined by the negative character of the Kutubu and cordilleran(Wahgi and Ramu system) troughs and the slightly negative Fly-Digoel platform. Although it is easily recognized that the overall Mesozoic tendency of these regions was negative, it is possible that future detailed work will show more variation in the character of movement during this very long interval than is now evident.

The Paleogene stabilization of the geosynclinal regime and the widespread emergence of the Fly-Digoel platform is also apparent on this chart, as well as the succeeding Lower Miocene phase of retrogressive taphrogenesis.

The orogenic phase of diastrophism, which gave rise to the inversion of the cordilleran geosynclinal troughs, had its inception during the Middle Miocene and is probably active at present. The Kaugel trough lay to the south of the main center of uplift and was not caught up in this uplift or inverted until the uppermost Upper Miocene. It did not become strongly positive until the Plio-Pleistocene when the upheaval of this trough contributed heavily to the thick Pliocene exogeosynclinal accumulations in the Purari basin and their subsequent folding.

4.3 CRUSTAL STRUCTURE OF THE OROGEN

This section is devoted to a discussion of a provisional cross section which I have prepared to illustrate the crustal structure of the New Guinea orogen. The value of such a crustal profile is twofold. In the first place it permits the folded and faulted structures of the orogen to be critically examined in a broader context; i.e., as an integral part of the earth's crust rather than mere superficial wrinkles of the earth's surface. Secondly, such a crustal profile may shed some light on the mechanism(s) of orogenic uplift.

An approximation of the crustal structure; i.e., the thickness of the crust T , can be made according to certain empirical relationships between T and the Bouguer gravity anomaly Δg such as have been worked out by Woollard (1959), (Woollard and Strange, 1962) and several other independent workers both in the United States and the U.S.S.R. These relationships have been found during the course of studies in regions where the crustal structure is known through seismic investigations. Here Woollard's (1962) linear relationship will be used; viz.,

$$T = T_0 - \left[\frac{\Delta g}{41.85 \Delta \rho} + h \right]$$

where:

T = crustal thickness.

T_0 = "normal" crustal thickness at zero Bouguer anomaly which is generally determined seismically

$\Delta\rho$ = density contrast between the crust (2.67) and the mantle (3.27) which is assumed to be constant
= 0.6 gm/cc

Δg = Bouguer gravity anomaly

h = Elevation of gravity stations in meters

In this preliminary study the consideration of these thickness relationships will be limited to a line corresponding to the structural profile illustrated in Plate 4 which traverses the New Guinea orogen from Wana in the Delta embayment northward to the Ramu Valley. Six gravity stations, which form part of a regional network now being established in the course of a special study conducted by the Geology Department, the University of Tasmania, are located along this section. The field observations were made by Mr. John Shirley.

The values of the free-air and simple Bouguer gravity anomalies are shown on Figure 37 for each of these stations. As would be expected, the free-air and Bouguer anomalies are both quite low in the Delta embayment region which is essentially at sea level. The free-air anomaly becomes positive across the main cordillera but is strongly negative at Dumpu which is located in the Ramu-Markham depression. As is generally the case the Bouguer anomaly profile is a mirror image of the topography. However, between Bundi and Dumpu the anomaly becomes still more negative and is an exception to the general relation. The significance of the excessively negative free-air and Bouguer anomalies in the Ramu Valley will be dealt with

GRAVITY PROFILE ACROSS THE NEW GUINEA CORDILLERA

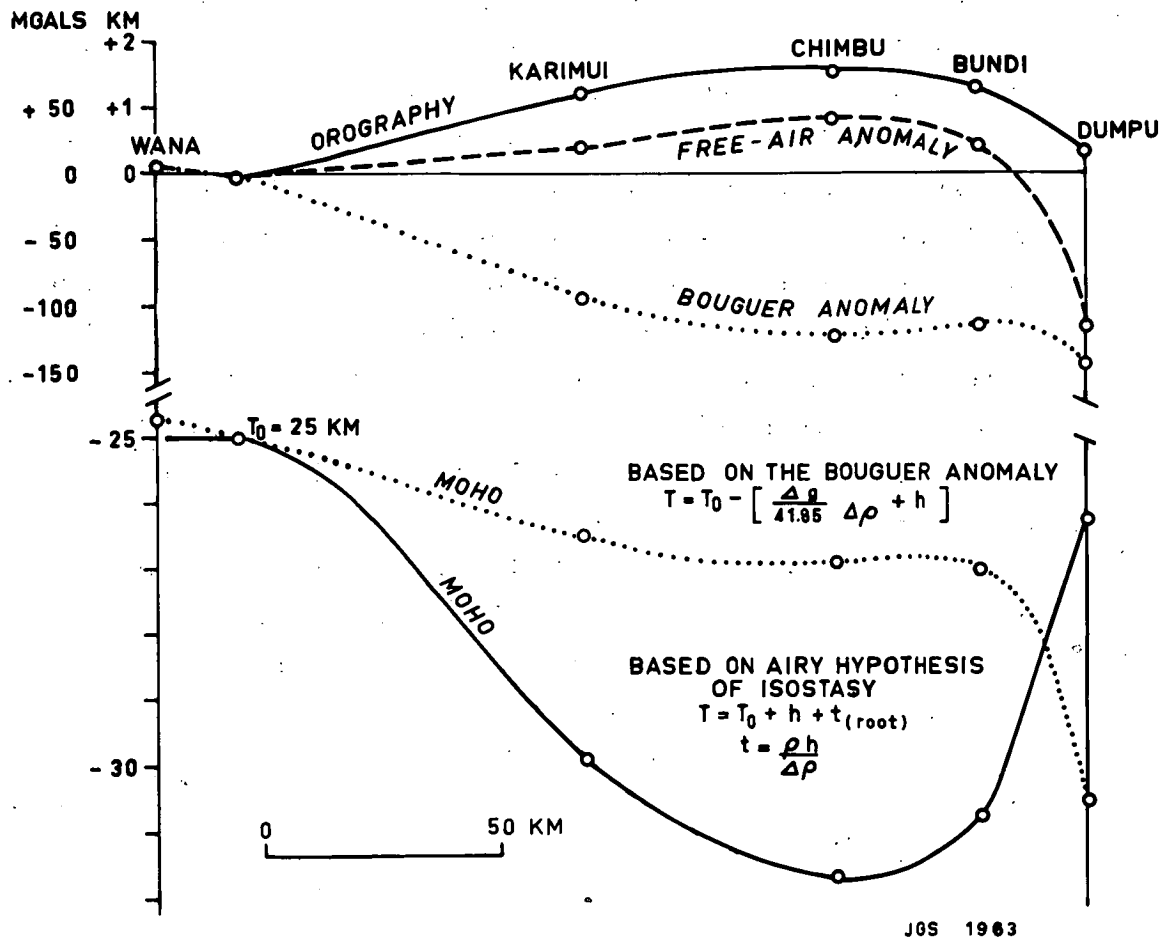


Figure 37

shortly.

An important difficulty in the specific application of Woollard's or any other empirical relation for deducing crustal thickness to New Guinea is the decision of what value to use for the thickness of the "normal" crust T_0 . At present the crustal thickness; i.e., the depth to the Moho has not been recorded seismically anywhere in the New Guinea region. Therefore, it is only possible to assume a likely value for the normal crustal thickness. In most cases it is the usual practice to assume T_0 equals 33 kilometers (Worzel and Shurbet, 1955) as has been done by Reilly (1962) who made a study of crustal structure in New Zealand which was based on empirical relations for determining crustal thickness. However, I think that 33 kilometers would be too high an average value for crustal thickness in an active orogenic terrain, particularly if crustal extension has played an important role in the evolution of that region. My opinion is supported to some extent by Officer's (1955) studies in the southwestern Pacific which indicated rather low average values of crustal thickness. For instance the thickness beneath New Zealand is thought to be 20-30 kilometers; 20 kilometers beneath the Lord Howe Rise; 25 kilometers along the East Cape-Kermadec-Tonga Ridge and 15-20 kilometers between New Zealand and the Solomon Islands. All these values are substantially less than the "normal" thickness of 33 kilometers.

No matter what value is assumed there may be substantial departures from the hypothetical values of T obtained and the actual thickness. However, the overall configuration of the Moho relative to a given datum will be the same regardless of the value used for T_0 .

In the course of the following computations I have assumed the crustal thickness $T_0 = 25$ kilometers in the Wana area of the Delta embayment region which is nearly at sea level and where both the Bouguer and free-air anomalies are very low. This region can be assumed to be in an approximate state of isostatic equilibrium. The figure of 25 kilometers has been obtained by the same relationship described in Section 3.1.4 and used to reconstruct the subgeosynclinal crust in the genetic profiles included in Section 4.5; i.e., assuming an original crust of 33 kilometers (thickness prior to taphrogenic rifting and stretching), with a density of 2.84 and with local isostatic compensation of columns with their tops at sea level. By referring to Plate 4a it is seen that the maximum accumulation of Mesozoic plus Tertiary sediments in the Delta embayment region is about 7 kilometers and possibly thicker to the north. Assuming a density of 2.3 for these sediments and isostatic equilibrium; the subgeosynclinal crust would then be 17-18 kilometers (Fig. 29) making a total upper crust of 25 kilometers (sediments + subgeosynclinal crust). Since in the following relations it is necessary to work with a two layer model (crust and mantle) rather than the three layer model (sediments, subgeosynclinal crust and mantle), as used for the geosynclinal reconstructions, a density of 2.67 will be used in further computations as an average density for all layers above the Moho.

Using these assumptions and the Bouguer gravity anomaly for each of the six gravity stations occurring along the structural profile in Plate 4, Woollard's relation is solved for T and the results are plotted on the schematic profile (Fig. 37) and the structural cross section in Plate 4b. It can be seen that on the

basis of the Bouguer anomaly there is a root ($t_{\text{root}} = T - T_0 - h$) of only 1.9 kilometers beneath the main cordillera at Chimbu. This would be the thickness of the root regardless of the value assumed for T_0 . According to Woollard's relation it appears that the root would be thickest under the Ramu Valley. This position is viewed tentatively, however, and it is felt that this is one locality where the structure of New Guinea may differ significantly from the regions for which Woollard formulated his empirical relationship.

A second approximation of the orogenic crustal structure was prepared on the assumption of isostatic equilibrium and again a "normal" crustal thickness of 25 kilometers according to the simple relation:

$$T = T_0 + h + t$$

where:

$$t = \text{thickness of the root} = \frac{\rho h}{\Delta \rho} \text{ (Heiskanen and Vening Meinesz, p. 136, 1958)}$$

$$\rho = 2.67 \text{ gm/cc}$$

$$\Delta \rho = 0.60 \text{ gm/cc}$$

The values of crustal thickness T obtained are also shown on Figure 37 and Plate 4a. This relationship was used to approximate the configuration of the Moho in all the structural profiles presented in Section 2.

The values of crustal thickness T are considerably greater than those obtained using the relation based on the Bouguer anomaly. For instance the crustal thickness at Chimbu is 33.2 kilometers which is 4.8 kilometers larger than the thickness obtained using the Bouguer anomaly. If the regional elevation of the central cordillera (2000 kilometers) rather than the elevation of Chimbu, which is in a deep valley, were used in this

relation, the thickness of the crust would be still greater and would include a root of nearly 9 kilometers.

On the other hand if complete isostatic equilibrium were achieved the Moho would be 3.3 kilometers higher beneath the Ramu Valley than indicated by the Bouguer relationship. It might be possible that this anti-root of ultrasima may extend even higher into the crust than either of these relationships indicate. The large negative values of the free-air and Bouguer anomalies which have been recorded in the Ramu Valley are typical of the anomalies which occur over modern rift valleys, particularly in the early stages of development. In such zones where crustal stretching is at a maximum the Moho rises in order to correct the large negative loads created in the upper levels of the crust. The relatively high degree of seismic activity occurring in the Ramu-Markham depression, as well as its morphology, also indicate that this region may at present be an active zone of stretching.

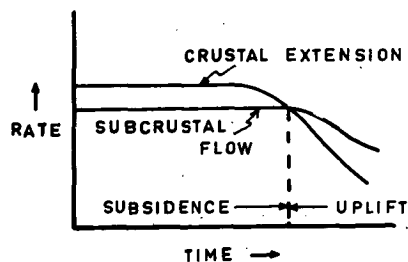
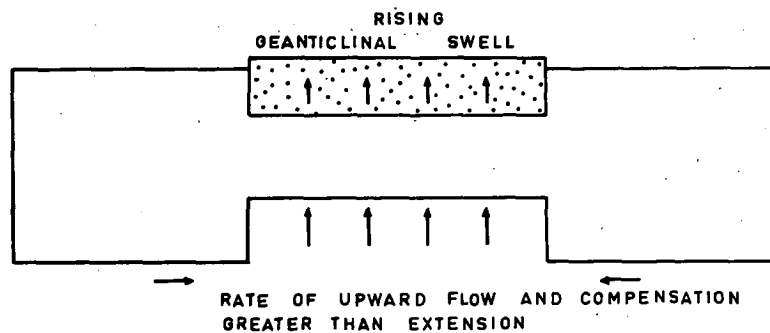
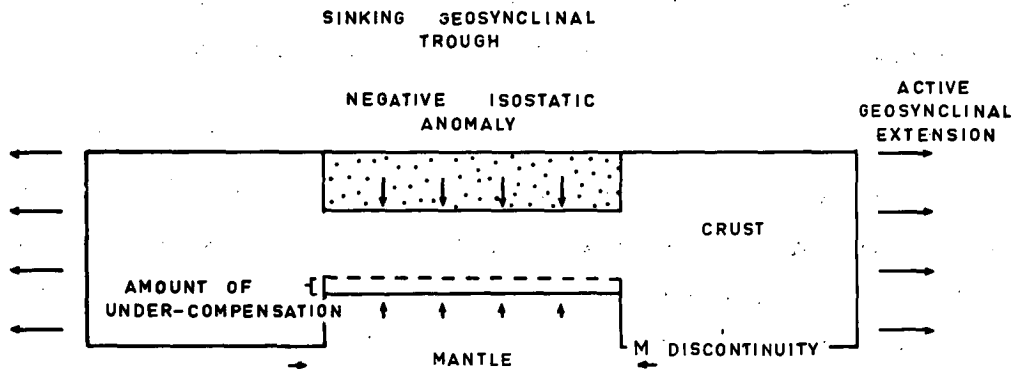
4.4 ORIGIN OF OSCILLATORY VERTICAL MOVEMENTS

4.4.1 Taphrogenic Phases of Diastrophism

Intrageosynclinal troughs.-- The evolution of vertical movements in a geosynclinal mobile belt can be represented in terms of a dynamic balance between the processes of crustal extension and sinking; sedimentation; and finally, isostatic compensation (Fig. 38). Rifting and stretching of the crust and the associated accumulation of sediments tends to destroy the isostatic balance of the crust and represents a relative negative load which is to some extent corrected as it develops by subcrustal flow of ultrabasic mantle material. True geosynclinal troughs are likely to exist only if the rate of crustal rifting, stretching and sinking is greater than the rate of isostatic correction. The rate of subcrustal flow, however, is thought to lag only slightly behind the rate of sinking, so that, as indicated in Section 3.1.4, the geosynclinal troughs are maintained in an approximate state of equilibrium.

Sedimentation in the Papuan intrageosynclinal troughs seems to have kept pace with the depression of the subgeosynclinal crust as is indicated by the generally neritic character of the sediments in these troughs.

ORIGIN OF VERTICAL MOVEMENT OF INTRAGEOSYNCLINAL TROUGHS



JGS 1963

Figure 38

Beloussov (1962) has emphasized that this relationship between subsidence and sedimentation can be shown to be true in the majority of geosynclinal troughs. There is certainly, as yet, no evidence of extensive leptogeosynclinal or "starved basin" deposits; i.e., radiolarian cherts, pelagic limestone and azoic shales, like those which are observed in the Alps (Trümpy, 1960) and clearly indicate that subsidence was outpacing sedimentation.

If for some reason the extensional stresses which maintain the geosynclinal sinking are in any way abated, subcrustal flow will soon correct the negative load imposed on the crust by the geosynclinal trough filled with sediments (Fig. 38). This correction necessitates the rise of the dense sub-Moho materials to higher levels beneath the geosynclinal troughs. There is, however, a significant difference between the flow at this stage and the compensation flow during the active phase of crustal stretching. In the latter case the ultramafic materials moved upward into a vacuity created by the stretching of the subgeosynclinal crust. However, with the cessation of stretching the thickness of this layer remains constant and any upward movement of the mantle will produce a sympathetic movement in the overlying crust. Consequently, the uppermost layers of the geosynclinal prism which originally lay at depths of about 2-300 meters below sea level would be raised much closer to sea level and there be manifested as geanticlinal swells. The amount of uplift partly depends upon the difference between the initial rates of sinking and compensation. As it stands, this mechanism could quite adequately explain the oscillatory nature of the vertical movements within the Papuan geosynclinal regime, particularly the

evolution of the intrageosynclinal troughs in the central foothills region; i.e., the Omati and Kutubu troughs; and the Erave-Wana and Darai swells. In the more mobile zones, as in the case of the central cordilleran region, these processes are somewhat more complicated.

Cordilleran massifs.-- There are several important contrasts between the central cordilleran massifs; i.e., the Kubor and Bismarck massifs and the geanticlinal swells located to the south in the central foothills region. In the first place the former are composed mainly of crystalline rocks and are associated with a much higher degree of mobilism than is evident in the central foothills region. Finally, although the gross pattern of movement of these blocks can be described as being oscillatory, it can be readily seen on Figure 36 that throughout the evolution of the geosynclinal system they have appeared to remain quite positive with the exception of a brief period during the Paleogene. In the following pages I will suggest how this rather peculiar pattern of movement might be explained by the mechanisms of uplift outlined thus far.

The positive movements of the cordilleran massif are consistent with the fundamental balance between crustal extension and isostatic compensation which is thought to have governed the evolution of vertical movements in the Papuan geosynclinal system, at least during the taphrogenic phases of diastrophism. I regard these massifs as horst-like fragments of the Paleozoic anorogenic platform which were split off and isolated from surrounding portions of the platform by bifurcating tensional fractures that developed during the Mesozoic initial phase of taphrogenesis. As such the vertical movements of these

blocks can be explained by a mechanism suggested by Carey (1958) for the uplift of the non-volcanic Ruwenzori massif in the east African rift system.

The positive character of these blocks is the natural consequence of their tectonic environment. Blocks such as the Kubor and Bismarck massifs are probably too small to command immediate isostatic equilibrium. If they are isolated in the center of an active rifting zone which represents substantial negative gravity load on the crust these blocks will rise higher than their surroundings, because the regional negative environment would be first corrected by a broad regional upwarp which would preserve the overall isostatic balance. These blocks would be located along the crest of this regional bulge. Even if the blocks would be large enough to command local compensation eventually, as long as geosynclinal stretching continues at a rate exceeding subcrustal flow, a large component of the adjustment will be at a regional scale and uplift of the cordilleras would be considerable. This relation between crustal extension and compensation is thought to have existed throughout the Mesozoic period of taphrogenesis and the Tertiary phase of retrogressive taphrogenesis and it is considered to be a quite adequate explanation for the positive relief of the Kubor and Bismarck massifs.

If the extensional stresses are dissipated, then it would be possible for subcrustal flow to affect local compensation of these blocks, lowering them to the level of their surroundings. For instance a temporary disruption of the tensional stress field producing crustal rifting may account for the lowering of these massifs during the late Cretaceous and Paleogene. It has already

been suggested that the complete absence of volcanism in western Papua and New Guinea during the Paleogene might also be attributed to a temporary decline of extensional stresses.

The rise of the cordilleran massifs during the orogenic phase of diastrophism was probably not due so much to the processes discussed here, but is rather attributed to the fact that these rocks were caught up in the general uplift associated with the inversion of the entire geosynclinal realm.

4.4.2 Orogenic Phase of Diastrophism

Uplift of the main cordillera.-- Although the uplift, which is an integral part of the dynamic balance between crustal extension, geosynclinal sinking and flow of the upper mantle is sufficient to cause the epeirogenic stabilization of geosynclinal terrains and the formation of relatively low (probably less than 500 meters) geanticlines such as the Erave-Wana and Darai swells, it may not be entirely adequate to produce the major positive vertical movements such as accompanied the development of the New Guinea cordillera. Specifically, it is doubtful whether at the onset of orogenesis in the Middle and Upper Miocene, the unbalance between crustal extension and compensation was great enough to induce the substantial uplift (2000-3000 meters) related to the inversion of the cordilleran intrageosynclinal troughs. With the exception of the Paleogene stabilization the cordilleran troughs were actively sinking for a period of at least 175 million years. This would allow more than ample time for the complete isostatic adjustment of the cordilleran troughs. Consequently, I suggest that in the cordilleran region

another mechanism has either enhanced the processes of uplift outlined in the previous pages or has been the sole agent of uplift.

Phase changes from high to lower density minerals in the mantle might provide the second mechanism of uplift, and one more compatible with the magnitude of orogenesis. Two main processes are possible depending on the model which one accepts for the upper mantle and the nature of the Moho; viz., the transition from eclogite to basalt as advocated by Lovering (1958) and Kennedy (1959) or the serpentinization of peridotites proposed by Hess (1955). Either of these phase changes could conceivably cause the uplift of a geosynclinal regime which has originated by extensional processes, such as the Papuan geosynclinal system.

By the end of the Lower Miocene some 12-17 kilometers of Mesozoic and Tertiary sediments and volcanogenic deposits had accumulated in the cordilleran troughs. The greatest amount of stretching, sinking and sedimentation was concentrated in the zone now occupied in the main cordillera. In their net effect these accumulations represented a considerable negative load on the crust and it is supposed that they were compensated to a large extent by the rise of upper-mantle materials. This upward migration would bring the ultrasima to cooler levels of the crust. At first the isogeotherms would move upward with the rising ultrasima. Eventually, however, this allochthonous mantle material would come to thermal equilibrium with the surrounding, cooler layers of the crust and the isogeotherms would be lowered. This situation would be greatly augmented if geosynclinal rifting and, therefore,

the rise of new ultrasima into the subgeosynclinal crust were curtailed. The final temperature of the subgeosynclinal ultrasima would be less than the temperature normally assumed to exist at the Moho beneath continents; i.e., 500-700°C. The decrease in temperature would be sufficient to trigger either of the above phase changes; conditions would be particularly suitable for serpentization of peridotites assuming the availability of sufficient quantities of water.

If on the other hand the upper mantle is assumed to be composed of eclogite, then the subgeosynclinal phase change to basalt would be enhanced by the decrease in pressure which would accompany the upward flow of the mantle. As de Sitter (1960) pointed out, hydrostatic pressure would be reduced still further, if regional tensile stresses were present.

Either of these phase changes would cause a volume increase of 10-25% and would produce a root of light rocks beneath the geosynclinal belt. In turn isostatic adjustment of this root of new basalt or serpentinite would cause uplift of orogenic proportions at the surface. The development of the mountain range and the formation of the root would proceed simultaneously.

If either of these phase changes is accepted as the mechanism promoting orogenic uplift, we then are faced with the problem of why such changes did not follow the earlier stages of geosynclinal sinking; i.e., the development of the Mesozoic Kutubu and cordilleran troughs. Perhaps they did and the Paleogene stabilization of the geosynclinal terrain may have been the result of phase changes. My present suggestion is that the conditions

suitable for either the serpentization of peridotite or the eclogite-basalt conversion were not achieved until at least the Middle Miocene and, then these conditions of temperature and pressure only existed in the present cordilleran region where prolonged Mesozoic and Tertiary crustal stretching and rifting caused the mantle to penetrate high into the crust in order to maintain isostatic balance.

I may have underestimated the potential of subcrustal flow, such as was proposed to have caused the uplift of the geanticlines, as a mechanism of orogenic uplift. It is important to recall that the root beneath the main cordillera, as determined from the Bouguer anomaly, is much smaller than that which would be required to support the mountains isostatic equilibrium (Fig.37). This relationship, which suggests that the cordillera may have been uplifted without the formation of a root, is consistent with the notion that orogenic uplift was initiated by vertical flow of the mantle in the subgeosynclinal regions. However, a root of lighter material, such as is thought to exist under most mountain systems, would still have to form. Again this could be accomplished by phase changes in the ultramylonite which penetrated the crust beneath the cordillera.

The origin of the forces promoting the uplift of orogenic belts is still one of the most fundamental and difficult problems to be solved by geologists. The ultimate solution will need to be based on a very careful quantitative examination of the relative rates and magnitudes of geosynclinal formation, isostatic compensation, uplift, and phase changes as well as consideration of many other geophysical parameters. The mechanism of

orogenic uplift which I have discussed represent only two possible solutions to the problem and are certainly not unique. For instance, I can not deny the possible application in New Guinea of the orogenic hypotheses, advocated by van Bemmelen (1954), Belousov (1962) and other tectonists, in which mountain building is thought to be provoked by magmatic "granites" that form in the mantle and rise, by virtue of their buoyancy, into the geosynclinal zones causing their inversion and deformation. I have, however, put some restrictions on the nature of the forces associated with orogenesis in western Papua and New Guinea. I have shown that, with the exception of features produced by translation and rotation, all of the structural characteristics of the New Guinea cordillera can be sufficiently explained in terms of vertical oscillatory movements of the crust and that the old vise concept of tectonics is superfluous. I have also reaffirmed and re-emphasized the intimate spatial relationship between geosynclinal troughs, and subsequent geanticlinal swells and cordilleras. Any acceptable hypothesis of orogenesis will have to account for this significant relationship.

4.5 GENETIC HISTORY OF VERTICAL OSCILLATORY MOVEMENTS

Plates 6 to 9 have been prepared to illustrate the genetic history of vertical oscillatory movements within the Papuan geosynclinal system. Both the nature and the mechanism of movement can be readily summarized by reference to these structural profiles.

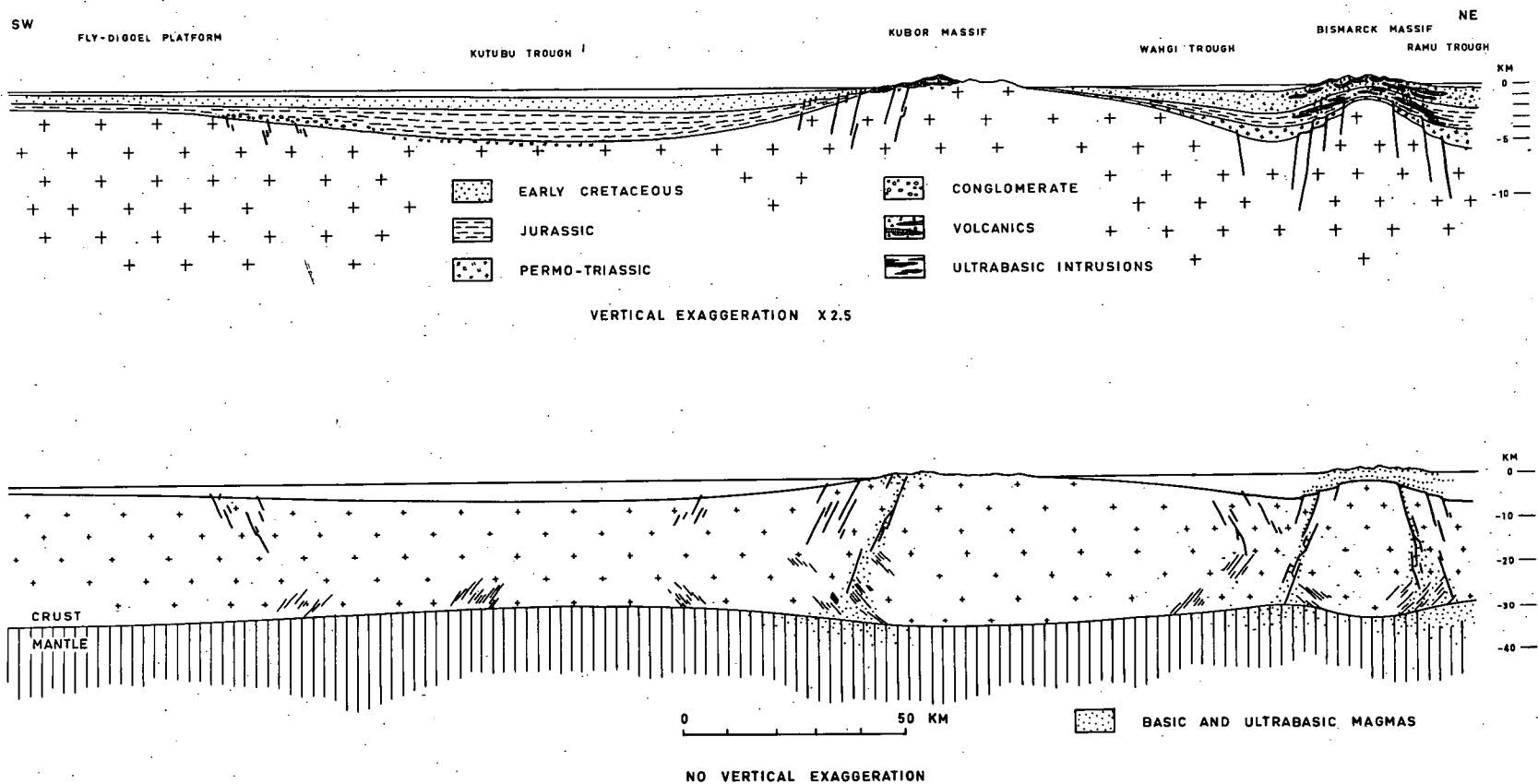
As I have explained in Section 3.1.4 these cross sections are based on three main assumptions: (1) the geosynclinal troughs and intervening geanticlinal highs developed in response to extensional rifting and stretching of a crustal plate of an originally uniform thickness; (2) this crustal plate or anorogenic platform is assumed to have had an original thickness of 33 kilometers; (3) the geosyncline developed in an approximate state of isostatic equilibrium.

4.5.1 Initial Taphrogenic Phase

Plate 6 represents the Jurassic and early Cretaceous development of the Papuan geosynclinal system. It can be seen that extensional stresses had already caused rifting and thinning in several localities within the limits of the original Papuan anorogenic platform. The rate of deformation was the greatest in the site of the present cordillera. There the extensional stresses gave

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INITIAL TAPHROGENIC PHASE -- TRIASSIC, JURASSIC, AND EARLY CRETACEOUS



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rise to tensional fracturing and the formation of a series of rift zones representing the incipient cordilleran troughs.

The fractures occurred in sufficient numbers and magnitude to form a network of fissures which penetrated the lower levels of the crust and perhaps even the upper mantle. This network of fissures provided channels for the ascent of basic and ultrabasic magmatic materials, as well as aqueous fluids into the upper levels of the crust.

The ultrabasic materials of the upper mantle rose beneath the troughs to compensate for the negative gravity load which was imposed at the surface by rifting, stretching and sedimentation.

Crustal extension accompanied by geosynclinal sinking continued throughout the early Cretaceous and followed the pattern initiated in the Triassic and Jurassic. Deep crustal fracturing and volcanism were probably especially active at this stage as indicated by the high proportion of volcanic materials in the early Cretaceous rocks of the central cordillera. A large portion of the ultrabasic rocks which occur in the western Bismarck Range may have been emplaced at that time.

The Kubor and Bismarck massifs were both isolated from adjacent stretching zones by deep fractures. Therefore, the crustal columns in each of these regions was essentially equal to that of the original platform. As a result of regional isostatic compensation these blocks remained positive throughout the taphrogenic phases of diastrophism.

It is important to note that although the Papuan geosynclinal system is thought to have widened as a result of this crustal extension, I have made no attempt to restore the geosynclinal belt to its original width in these profiles. Such a reconstruction would require among other things more detailed stratigraphic information than is now available. In this sense the profiles represent a compromise between the extensionist, fixistic, and compressionist schools of tectonic thought.

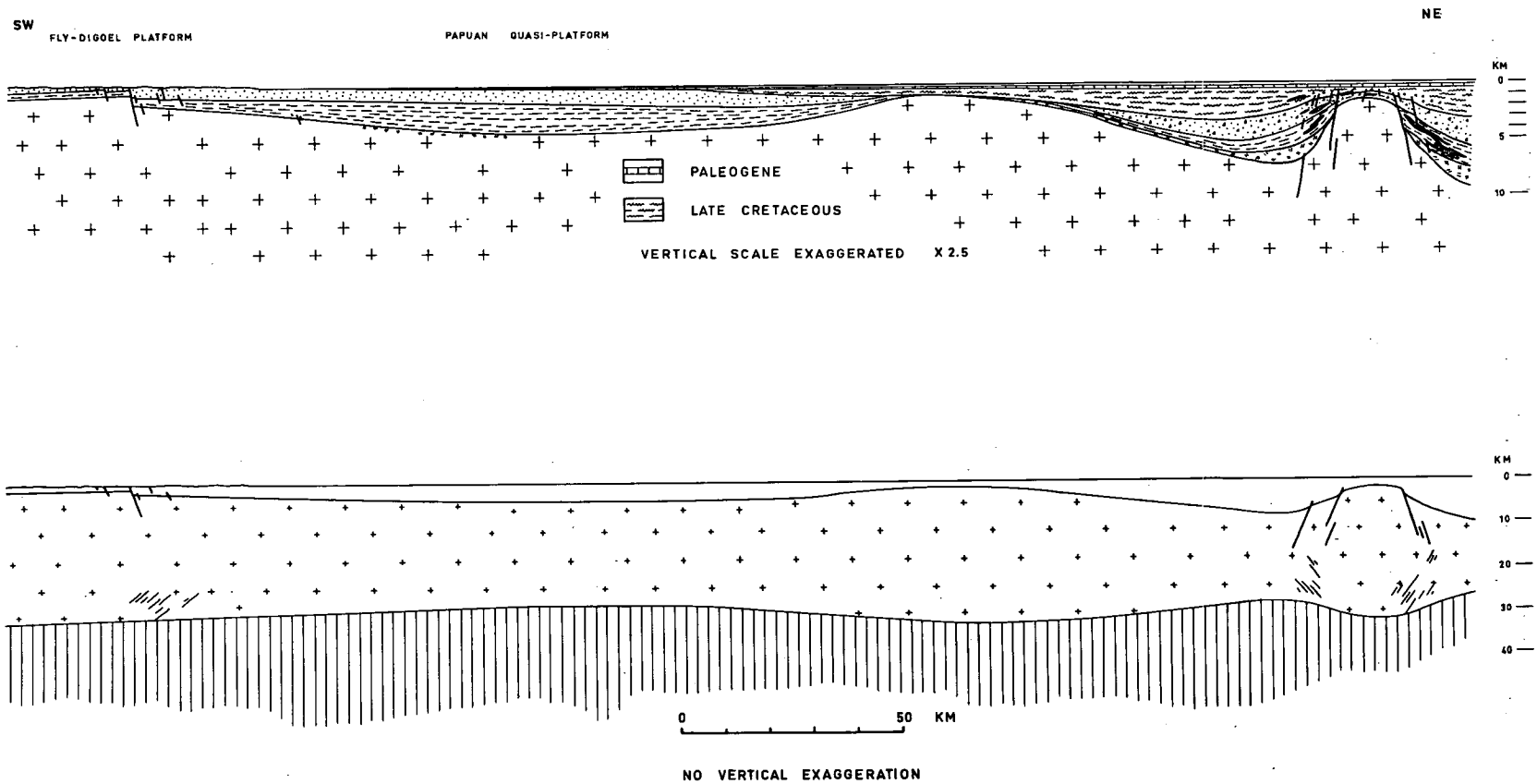
4.5.2 Stabilization Phase

I have repeatedly argued that the extensional stresses producing geosynclinal rifting and stretching were greatly reduced in the Paleogene. As a result the subcrustal flow maintaining isostatic balance was able to correct completely the regional negative environment imposed by crustal rifting. The Kutubu trough was, therefore, raised and stabilized to form an extension of the Fly-Digoel platform, the Papuan quasi-platform (Plate 7). The Fly-Digoel platform was itself somewhat raised and became emergent in response to the dissipation of the extensional stresses. Isostatic adjustments also occurred in the central cordilleran region. The Wahgi trough rose to some extent but did not become emergent. The cordilleran massifs subsided to correspond to the regional level of equilibrium.

Volcanism was not active during the Paleogene, presumably because of the absence of tensional stresses that provide an optimum environment for magmatic processes.

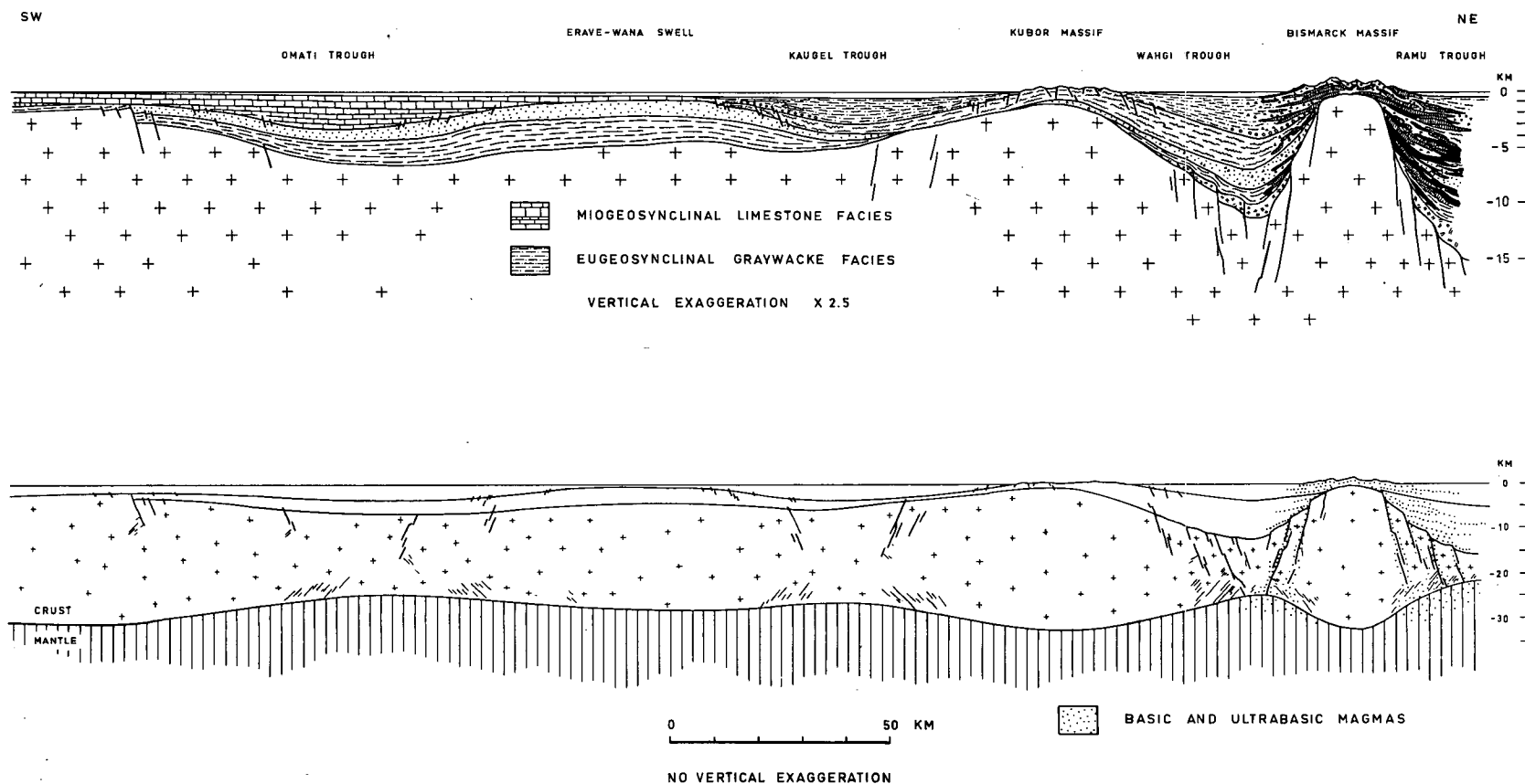
DIASTROPHIC EVOLUTION OF THE PAPUAN GEOSYNCLINAL SYSTEM

PALEOGENE STABILIZATION PHASE



DIASTROPHIC EVOLUTION OF THE PAPUAN GEOSYNCLINAL SYSTEM

LOWER MIOCENE RETROGRESSIVE TAPHROGENIC PHASE



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4.5.3 Retrogressive Taphrogenic Phase

After this brief respite extensional stresses were rejuvenated in the Lower Miocene and a new and vigorous phase of geosynclinal sinking and volcanism began (Plate 8). Geosynclinal rifting and stretching at this stage was most pronounced in the cordilleran region. In the central foothills the remobilization of the old geosynclinal regime was less intensive than that in the former region. However, the Omati and Kaugel troughs developed as a result of some element of rifting which was concentrated along the margins of the older Kutubu trough. The Erave-Wana swell separated these two troughs and represented a remnant of the Paleogene quasi-platform.

The Middle Miocene epoch marked a transition between the taphrogenic and orogenic phases of diastrophism. Tensional rifting and geosynclinal sinking still occurred along the southern margin of the Kaugel trough. However, by this time the Kubor and Bismarck massifs had consolidated into a single unit which was being uplifted.

4.5.4 Orogenic Phase

During the Upper Miocene the tendency of vertical movements became completely reversed and geosynclinal subsidence gave way to orogenic uplift. A limited amount of subsidence, however, did continue in the exogeosynclinal zones paralleling the axis of the orogen.

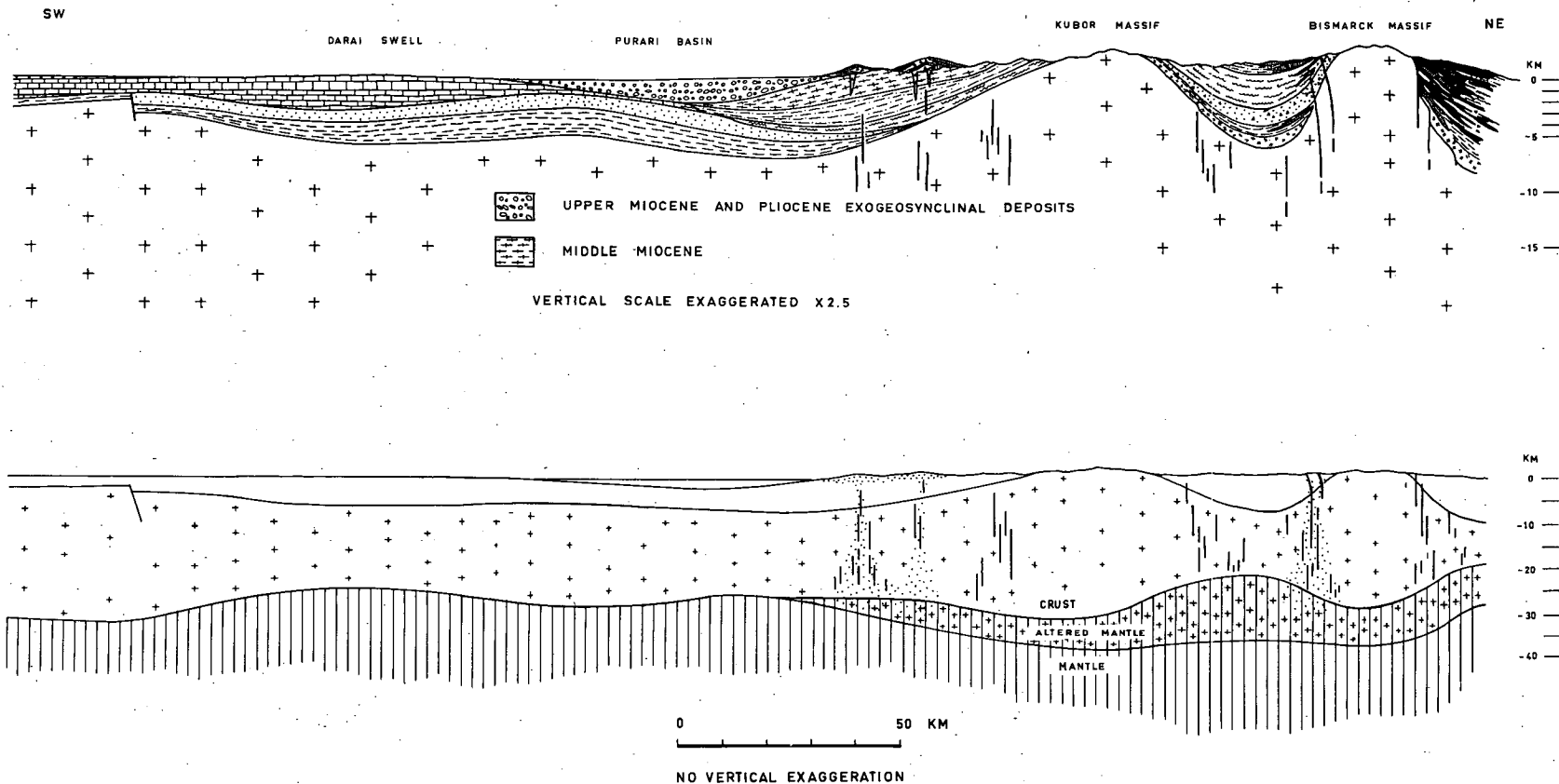
As I have suggested previously the uplift of the main cordillera may have initiated by phase changes within the mantle under the geosynclinal troughs. Either serpentinization of peridotite or the eclogite-basalt

transformation would produce a light root beneath the geosyncline which would promote isostatic orogenic uplift. The configuration of such a root of new crust is illustrated schematically on Plate 9.

The uplift of the cordillera was accomplished along vertical zones of flow such as illustrated in Figure 21. In regions where this movement was most rapid; i.e., along the margins of the cordilleran massifs and along the southern margin of the main cordillera, uplift proceeded along zones of fractures that were probably enhanced by a regional tensional stress environment. In many instances, particularly along the southern margin of the cordillera, these fractures also provided a suitable passage for the rise of andesite magmas and controlled the position of many of the Pleistocene volcanoes in western Papua, notably along the zone separating the foothills from the central cordillera.

As morphogenic uplift in the central cordillera proceeded outward from a nucleus about the Bismarck and Kubor massifs, the Kaugel trough was raised and tilted southward. As a result of this tilting the Mesozoic to Tertiary sedimentary sequence which had accumulated in the trough began to creep southward off the flanks of the main cordillera and toward the exogeosynclinal troughs. A very large part of the movements took place along a décollement near the base of the sedimentary sequence. Both the allochthonous sheet and the exogeosynclinal deposits were folded as a consequence of this lateral movement.

DIASTROPHIC EVOLUTION OF THE PAPUAN GEOSYNCLINAL SYSTEM

OROGENIC PHASE -- UPPER MIOCENE TO QUATERNARY

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4.6 RELATIONSHIP OF HORIZONTAL AND VERTICAL MOVEMENTS

In the preceding discussion of the nature and possible origins of vertical and horizontal movements I have only hinted at the spatial and temporal relations of these movements and their relative importance in the diastrophic evolution of western Papua and New Guinea. These relations will be considered in the ensuing pages.

It is my contention that crustal extension has been the most fundamental mechanism in the diastrophic evolution of western Papua and New Guinea and has had a significant influence on both the processes of taphrogenesis and orogenesis. The other movements which have played a role in the development of the orogen; i.e., folding and faulting; simple shear; translation and rotation, all have been superimposed on the basic extensional framework.

I have already shown that the widespread negative vertical movements of the crust which dominated the taphrogenic phases of diastrophism were the direct result of rifting and stretching. There is also some significant evidence to suggest that horizontal extensional stresses were not dissipated at the end of the taphrogenic phases of diastrophism but persisted throughout the Upper Miocene to Recent times and may have contributed to the orogenic

uplift of the main New Guinea cordillera:

1. The step-like structural pattern of the western cordillera region and its steep southern flank (Section 2.5; Figs. 26 and 27) has been interpreted to mean that block faulting, presumably related to tensional failure of the crust, dominated the paroxysmal stage of orogenesis in that region.
2. The main volcanic lineament developed in western Papua is still another indication of the possible importance of tensile stresses in the uplift of the orogen. As was described in Section 1.1.3 the lineament strikes in a westerly direction paralleling the central cordillera and contains ten of the seventeen Pleistocene to Recent volcanoes (Fig.1). It separates the central cordillera and the foothills along a front of approximately 300 kilometers. It is also quite significant that this zone is contiguous with the southern margin of the western cordillera which is thought to be controlled by important block faulting. The presence of these volcanoes is interpreted to mean that a system of deep fractures, presumably caused by tensile stresses, separates the central cordillera and the foothills regions. In the Pleistocene these fractures allowed the upward migration of andesitic and basaltic magmas to the surface. The large difference in the amount of vertical movement between the central cordillera and the central foothills (ca. 1000 to 1500 m.) was accommodated along this fault zone.
3. The high seismicity and the morphology of the Ramu-Markham and Sepik depressions suggest that this zone also may be the site of active rifting. As I have shown earlier, the gravity anomalies observed in the Ramu-Markham Valley are consistent with this interpretation.

Hence, it appears that vertical movements of the crust, both in the taphrogenic and orogenic phases of diastrophism, were strongly influenced by and, in fact, subordinate to extensional rifting and stretching. In the first place the rift zones defined the oscillating tectonic units; i.e., the intrageosynclinal troughs and geanticlines. Furthermore, the differential movement between the units for the most part was accommodated along the marginal rift zones. Particularly in the taphrogenic phases of diastrophism, the oscillations of the troughs and geanticlines may have been triggered by fluctuations in the intensity of extensional stresses. Finally, it is possible that extensional stresses may have given rise to a pressure-temperature environment in the upper mantle which would have provoked phase changes in the ultrasilica that, in turn, might have promoted uplift of orogenic proportions. Again much of the vertical movement was accommodated along zones of weakness which were once the rift margins of the Papuan geosynclinal system.

A comparison of the relative magnitudes of movements also points to the conclusion that vertical diastrophic processes are subordinate to horizontal mechanisms. The magnitude of vertical movements in western Papuan and New Guinea can be bracketed within rather narrow limits. In the central cordilleran region, for instance, the total subsidence during the Triassic to Lower Miocene taphrogenic phases was likely to have been between 12 to 17 kilometers. Uplift during the Upper Miocene to Recent orogenic was in the order of 2.5 to 4 kilometers.

Horizontal movements associated with the development of orogenic belts such as New Guinea are as much as one

or even two orders of magnitude greater than these vertical movements. In New Zealand horizontal movement along the Alpine fault has been about 480 kilometers since the Jurassic (Wellman, 1956) and movement along the San Andreas Fault in southern California has been 260 kilometers since the earliest Miocene (Crowell, 1962).

As outlined in Section 3.2.5 the geologic information in western Papua is not sufficient to make an estimate of the magnitude of horizontal movements implied by the fold patterns. In light of the postulated eastward drift of Australia and New Guinea horizontal movements may be great indeed. I do not imply, however, that some 6000 kilometers of lateral movement necessarily would be expressed in the pattern of folding and faulting in New Guinea. The bulk of this movement was most likely accomplished by viscous flow in the mantle and the strains which were propagated into the crust may represent only a small portion of total deformation associated with the eastward drift of New Guinea and Australia.

These few examples indicate quite sufficiently that horizontal movements are far greater in magnitude and of a more fundamental nature than vertical movements. Even the horizontal movements associated with the extensional widening of the Papuan geosynclinal system, that may have been in the order of 80 kilometers, are considerably greater than the vertical movements.

The fundamental importance of horizontal movements is also substantiated by chronological considerations. Horizontal movements are almost always of a secular nature and play an important role throughout the entire evolution of a mobile belt. In contrast vertical movements are of

short duration, spasmodic and reversible. As Carey (1962) points out the features formed by horizontal movements can range through three to four orders of magnitude beginning with graben (10^5 yrs.) through to rhombochasms and megashears (10^9 yrs.). The uplift of orogens is of a much smaller duration (10^5 - 10^7 yrs.).

In New Guinea horizontal movements have been active from at least the Triassic and are probably quite active at present. On the other hand there have been several very distinct phases of oscillatory movements during the same interval (Fig.36). Even the more spectacular phase of orogenesis, including primary tectogenesis, has been of a very short duration (ca. 12-15 million years). Although these rapid vertical movements have tended to obscure the more basic horizontal movements, the latter movements have had a strong influence on the more superficial folding and faulting and have left their mark in the sigmoidal, en échelon and intersecting tectonic patterns.

As I see it, the hierarchy of crustal movements which have governed the diastrophic evolution of western Papua and New Guinea can be summarized as follows:

1. Horizontal movements

A. Extensional rifting and stretching of the crust is considered to be the mechanism which roughed out the fundamental framework of the Mesozoic to Tertiary Papuan geosynclinal system and, consequently, had a profound influence on the subsequent development of the orogen. In eastern Papua extensional stresses were of sufficient magnitude to cause the separation of the Owen Stanley and New Britain blocks and the formation of the Huon speno-

chasm. The expansion of the earth or subcrustal convection currents could produce such rifting.

B. Simple shear deformation about a vertical intermediate stress or "roller" axis has been superimposed on the extensional framework. The effects of this deformation are particularly apparent in the structures formed during the orogenic phase of diastrophism (i.e., cordilleran anticlinoria and the foreland folded belt), however, more detailed stratigraphic work will probably show that simple shear deformation also had a significant effect on the taphrogenic phases of diastrophism. The postulated translational displacements along the Sepik and Ramu-Markham lineaments and the rotational displacements of the New Britain and Owen Stanley blocks are related to this simple shear deformation which again could be the result of either the expansion of the earth or subcrustal convection currents.

2. Vertical movements

The areal extent, chronology and mechanisms of vertical movements in Papua and New Guinea have been controlled by the extensional geosynclinal framework. The dominantly negative movements characterizing the taphrogenic phases of orogenesis were the direct result of crustal rifting and stretching. The areas of maximum uplift during the orogenic phase of diastrophism were defined by the earlier extensional framework. Uplift, particularly during taphrogenesis, may have been initiated to some extent by variations in the intensity of crustal extension, but the main orogenic uplift was likely to have been due to phase changes in the upper mantle. Nevertheless, the physico-chemical conditions promoting these transformations are

thought to have been met only beneath the rifting geosynclinal zones.

A. The primary tectogenesis or folding that accompanied the orogenic phase of diastrophism was the direct manifestation of vertical movements of the crust, although much of the form of the primary structures, particularly the central cordilleran anticlinoria, was inherited from the earlier geosynclinal patterns controlled by extensional stresses.

B. Secondary tectogenesis stands at the bottom of the hierarchy of crustal movements in western Papua and New Guinea both from the standpoint of magnitude and duration of movement. The foreland folding that falls into this category resulted from local compressional stresses developed in the allochthonous sedimentary sheet sliding off the main orogenic anticlinoria. The distribution and configuration of the foreland belt was controlled, although in a rather passive sense, by geosynclinal rifting.

Both primary and secondary structures bear the stamp of more fundamental horizontal movements; viz., sigmoidal plans, intersecting trends and the horst-like form of the main cordillera, all indicate that horizontal movements have strongly influenced the patterns of faulting and folding.

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